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— FINAL REPORT —

SPACE STATION AUTOMATION STUDY
AUTOMATION REQUIREMENTS DERIVED FROM SPACE MANUFACTURING CONCEPTS

VOLUME II
TECHNICAL REPORT

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GENERAL ELECTRIC GK08134

CONTENTS

1.0 INTRODUCTION

The purpose of the Space Station Automation Study is to develop informed technical guidance to NASA in the use of autonomy and autonomous systems to implement space station functions.

The study organization is shown in Figure 1.0-1. NASA headquarters formed and convened a panel of recognized expert technologists in Automation, Space Science and Aerospace Engineering. CAL SPACE was assigned the responsibility for study management, and for convening and directing a University/Industry Committee to produce the Space Station Automation Plan. A Senior Technical Committee, chaired by Dr. Robert Frosch, was appointed to provide top level technical guidance.

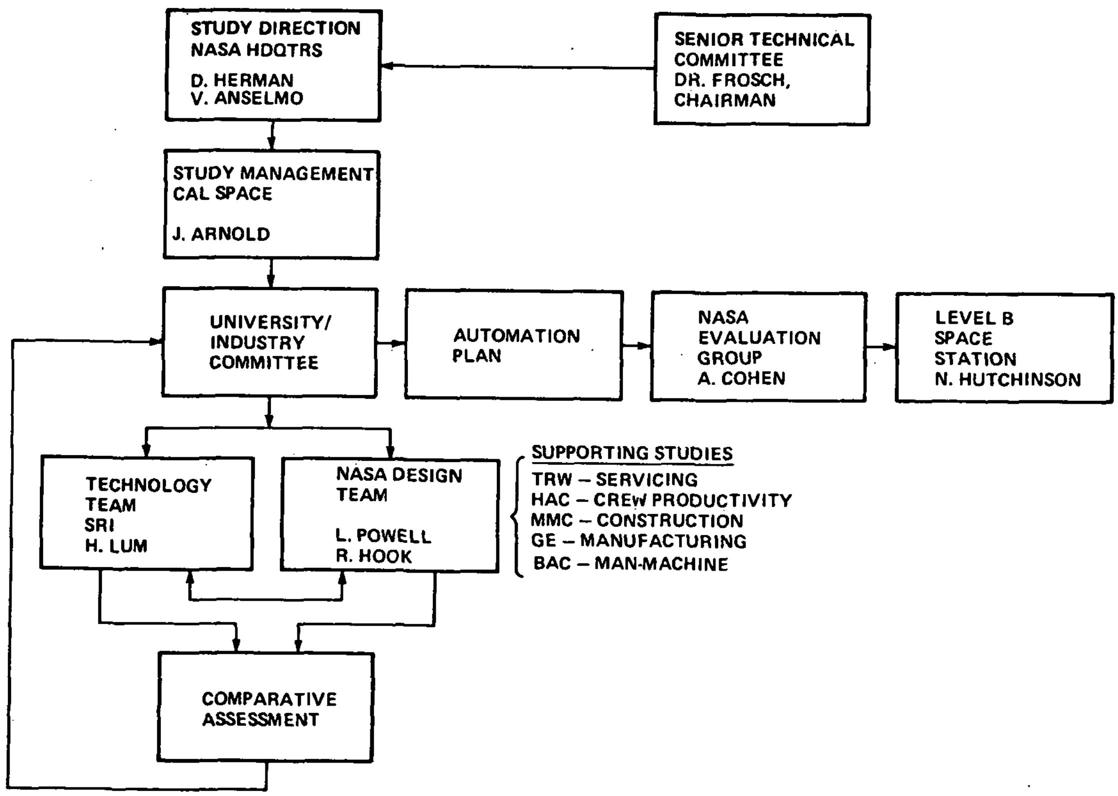

Figure 1.0-1. Space Station Automation Study Organization

SRI International was assigned to produce quality focused technology forecasts supporting panel analyses and guiding system concept design.

A NASA Design Team was convened to study the automation of remote space operations to produce innovative, technologically advanced automation concepts and system designs which will strengthen NASA understanding of practical autonomy and autonomous systems. Five Aerospace Contractors, TRW, GE, HAC, MMC and BAC, were assigned to this team.

The General Electric Company was assigned to assess automation technology required for remote operations, including manufacturing applications. In carrying out this assignment, GE assessed over one hundred potential Space Station missions through an extensive review of proposed Space Station experiments and manufacturing concepts. Subsequent meetings of the NASA Design Team resulted in the direction to proceed with in-depth development of automation requirements for two manufacturing design concepts:

(1) Gallium Arsenide Electroepitaxial Crystal Production and Wafer Manufacturing Facility

(2) Gallium Arsenide VLSI Microelectronics Chip Processing Facility

Figure 1.Ø-2 provides a functional overview of the ultimate design concept incorporating the two manufacturing facilities on space station. For the purpose of this study, the concepts were studied separately. This separation allowed conclusions and results to be determined in independent time frames without dependent cross ties.

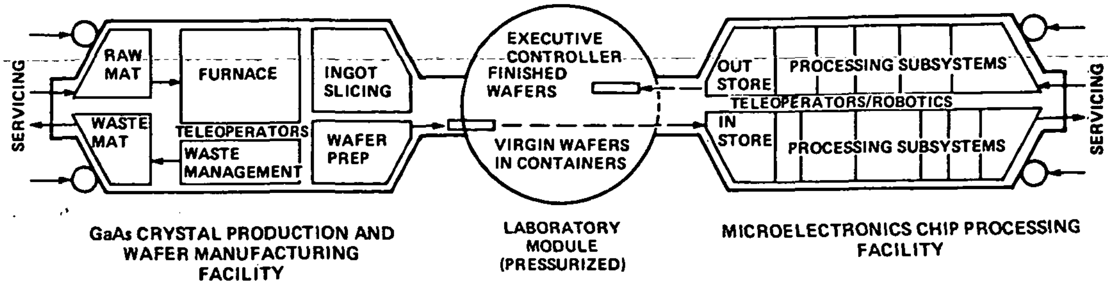

Figure 1.0-2 Overview Of The GaAs Manufacturing Facilities Concepts

Each facility would be developed in an evolutionary step-by-step process. As they are developed, more and more automation would be incorporated, evolving towards a full automation, including maintenance, repair and refurbishment functions.

Ultimately, in the year 2000 + time frame, it would be logical that both facilities could be mated to a common, standard space station pressurized laboratory module. The part time crew would tend the two facilities from the laboratory module, where all computer functions of process control and data display would be performed, and quality control checks and management of the finished products accomplished. Either or both facilities could be operated remotely from the Space Station, however, on separately powered, unmanned free-flying or tethered platforms, with control and data flow accomplished by RF communications with the Space Station or with ground facilities.

Both manufacturing facilities would be contained in enclosed structures as shown to help manage waste products and contamination, and to facilitate man-tended repairs and equipment upgrades.

1.1 BACKGROUND

The electroepitaxial process grows crystals in a low temperature furnace into ingots. These ingots, typically three to five inches in diameter, are then sliced into very thin wafers. The process provides defect free Gallium Arsenide (GaAs) wafers when accomplished in a gravity-free environment. In the second concept, many Very Large Scale Integrated (VLSI) circuits (chips) are typically processed on each wafer at the same time.

The two concepts were chosen for the main reason that they both require a very high degree of automation, and therefore involve extensive use of teleoperators, robotics, process mechanization, and artificial intelligence. They cover both a raw material process and a sophisticated multi-step process and are therefore highly representative of the kinds of difficult operation, maintenance, and repair challenges which can be expected for any type of space manufacturing facility. The automation techniques which would be developed for these space missions will provide direct benefits in the design of future ground-based automated factories to be used for a wide variety of materials processing and manufacturing applications.

Supporting reasons for selecting the two concepts are:

(1) There is a growing demand for faster, larger, and radiation hardened Integrated Circuits for which Gallium Arsenide has superior characteristics over silicon.

(2) An ultra-clean environment is necessary for efficient electroepitaxial crystal growth (ECG) and manufacturing of GaAs products. Additionally ECG requires a microgravity environment. On earth, ECG can only grow crystals of small size and value because of gravity-induced convection currents.

(3) The two concepts are compatible with each other. Although the Crystal Production/Wafer Manufacturing Facility could probably be flown five years before the Microelectronics Chip Processing Facility, eventually the product of one would provide the wafers to be processed into chips by the other.

The study results, although specifically addressing crystal growth and chip production, identify generic areas which will require significant further study for any planned future manufacturing in space. While cost analysis is beyond the scope of this report, the economics and benefits of any space manufacturing facility must be closely analyzed. The success of Space Station will be determined to a large extent by the programs ability to stimulate development of advanced technologies and fully develop the commercial potential of space. Advanced technologies for the automation of maintenance, repair, and refurbishment activities, as well as contamination control and waste removal represent major technological challenges to any space based manufacturing facility. Advanced designs of space manufacturing facilities will employ a high degree of automation, however the initial designs will be based on state-of-the-art hard automation such as terrestrial factories are employing and will grow and evolve as space and terrestrial technologies mature.

The unique aspects of a space manufacturing facility compared to a similar terrestrial factory, include the inability to bring in technicians and specialists for maintenance and malfunction repair. Therefore the advanced automation technology requirements identified by the study are those systems required to remotely monitor, diagnose, and automatically reconfigure, maintain and repair in the event of malfunction. These requirements embrace a broad spectrum of enabling technologies ranging from ultimate expert systems for monitoring, diagnosis and reconfiguration to teleoperation and robotic manipulative systems to perform manufacturing, servicing and repair under remote control from either the Space Station or ground.

1.2 SCOPE OF STUDY

The study statement of work is contained in Appendix A. The Contracting Agency was NASA Langley Research Center. Mr. Ray Hook and Mr. Al Meintel of NASA provided contract and technical direction.

The GE portion of the study was led by the Space Systems Division, but also utilized the corporate experience in manufacturing and automation in other GE divisions. The GE work plan is shown in Figure 1.2-1.

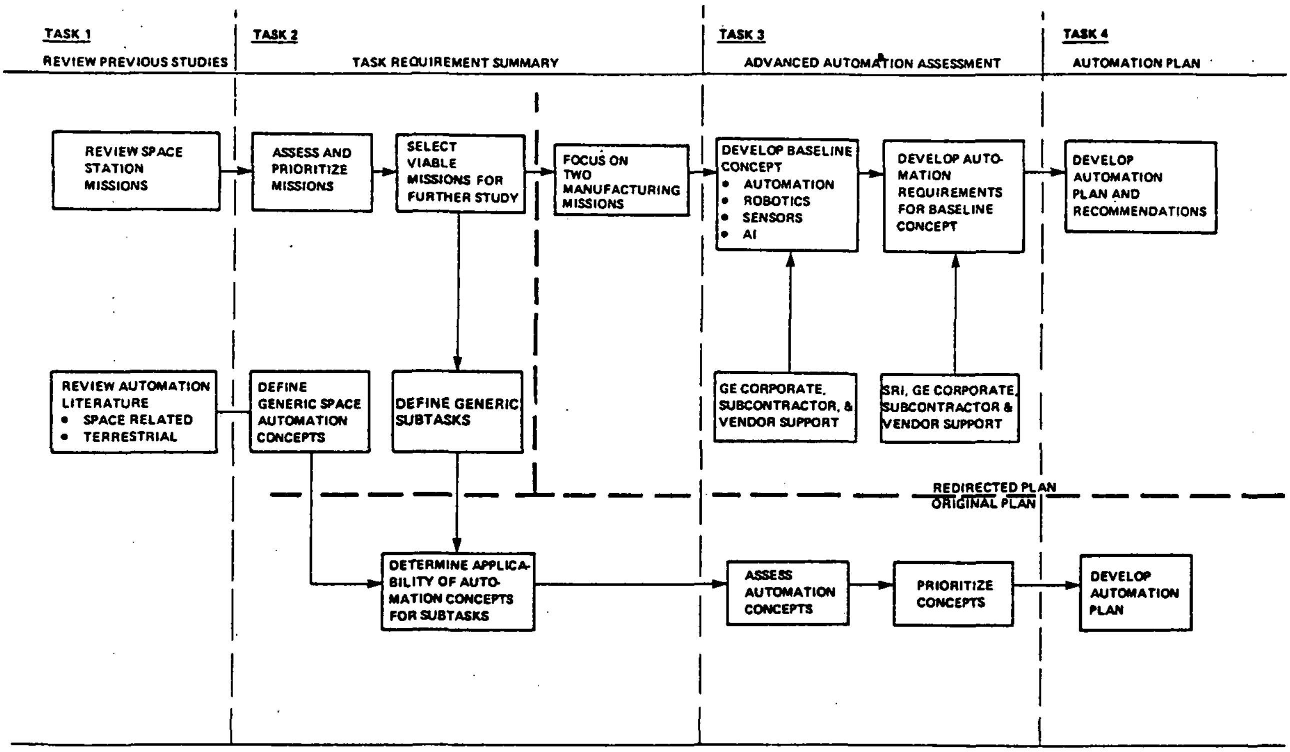

Figure 1.2-1 GE Space Station Automation Study Work Plan

Tasks 1 and 2 were accomplished in accordance with the statement of work and the work plan. At the July meeting of the NASA Design Team, where the results of Task 2 were presented, it became evident that a more in-depth focus on automation concepts

for two manufacturing missions would yield better results than a broader study of concepts developed for generic subtasks. Therefore, a redirection of the study plan was followed, as shown in Figure 1.2-1.

A further discussion of the study methodology is presented in Section 2.Ø, Mission Selection.

1.3 SCHEDULE

The overall study schedule is shown in Figure 1.3-1. The delivery of the final version of this Technical Report, together with an Executive Summary Report, completes the commitment of contract deliverables by GE. However, GE will continue to provide technical support to SRI and CAL SPACE until the end of the study on 1 April 1985.

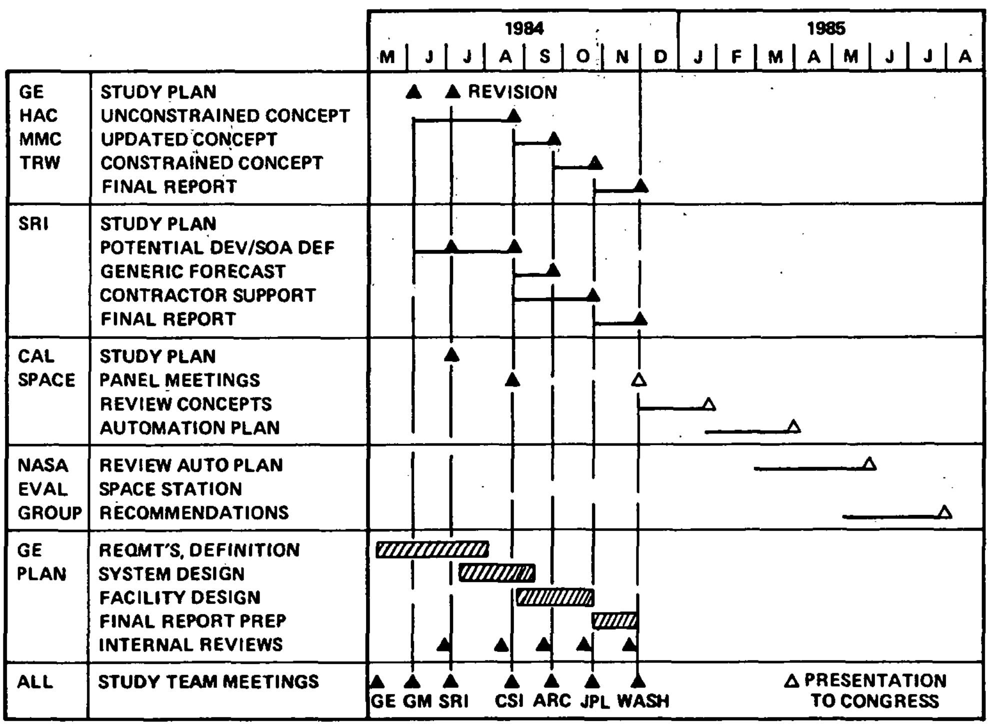

Figure 1.3-1. SSAS Study Schedule

1.4 GE STUDY TEAM

A GE Study Team was formed immediately after the first meeting of the NASA Design Team in May, 1984. The Study Team organization is shown in Figure 1.4-1.

The team participated in numerous meetings of the NASA Design Team and CAL SPACE Automation Study Team. A summary of these meetings is contained in Figure 1.4-2.

The GE Study Team worked with Microgravity Research Associates (MRA), and with other GE Divisions and NASA Centers throughout the study. Numerous working meetings were also held with manufacturers of microelectronics processing equipment. Figure 1.4-3 summarizes these working meetings.

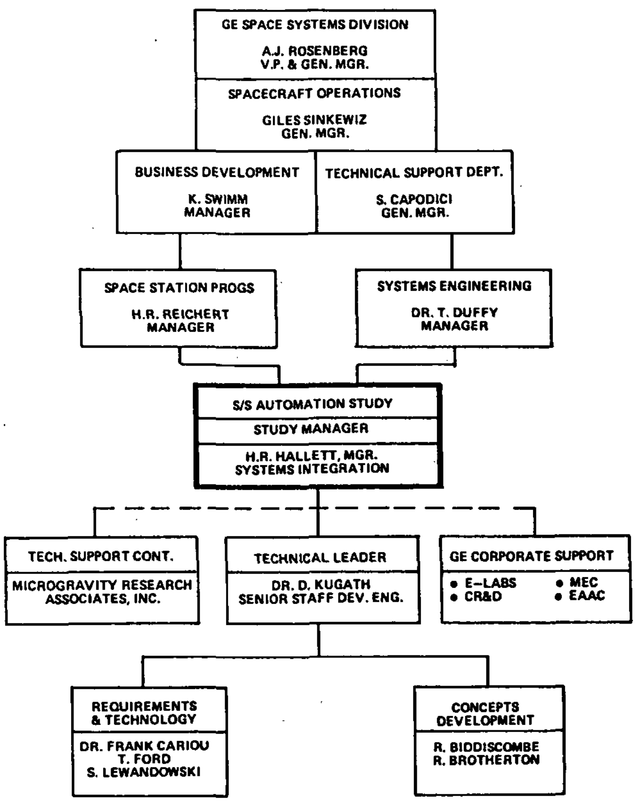

Figure 1.4-1 GE Study Team Organization

NASA WORKING GROUP MEETINGS

	DATES (1984)	LOCATION	GE ATTENDEES
NASA WORKING GROUP MEETINGS	22, 23 MAY	GE SPACE SYSTEMS DIV., VALLEY FORGE, PA.	REICHERT, HALLETT, KUGATH } SSD RUSSELL MEC STRUMAR EAAC BUTTERS RVSD
	7, 8 JUNE	GENERAL MOTORS, DETROIT, MICH.	HALLETT KUGATH
	10, 11 JULY	SRI, INC. MENLO PARK, CAL.	KUGATH
	22, 23 AUGUST	CAL SPACE, LA JOLLA, CAL.	HALLETT KUGATH
	1, 2 OCT	NASA ARC, MOFFETT FIELD, CAL.	HALLETT KUGATH
	23, 24 OCT	NASA JPL, PASADENA, CAL.	WATSON HALLETT KUGATH
	27, 28 NOV.	NASA JSC, HOUSTON, TEXAS	REICHERT KUGATH HALLETT WATSON
CAL SPACE MEETINGS	20, 21 AUG	CAL SPACE, LA JOLLA, CAL.	KUGATH HALLETT
	25, 26 OCT	CAL SPACE, LA JOLLA, CAL.	KUGATH HALLETT
	TBD	CAL SPACE, TBD	HALLETT

Figure 1.4-2 SSAS Team Meetings Summary

DATES (1984)	LOCATION/SUBJECT	GE ATTENDEES
8 MAY	GE INDUSTRIAL ELECTRONICS DEVELOPMENT LABORATORY (IEDL) CHARLOTTESVILLE, VA: TELE-OPERATOR, ROBOTICS STATE OF ART & CONTROL DEV.	HALLETT SSD SCHROEDER, IEDL
19 JUNE	NASA GSFC, GREENBELT, MD. (C. MACKENKIE) EARTH OBSERVATORY SYSTEM/X-RAY TIMING EXPERIMENT AUTOMATION	KUGATH
12 JULY	NASA/JPL, PASADENA, CAL. (J. GRAF) EARTH OBSERVATORY SYSTEM AUTOMATION	KUGATH
28 JUNE	NASA MSFC, HUNTSVILLE, ALA. (K. TAYLOR): STS MANUFACTURING PROCESSING IN SPACE (MPS) DEVELOPMENT	HALLETT KUGATH
28 JUNE	MRA, INC., HUNTSVILLE, ALA. (R. PACE); STS ELECTROEPITAXIAL CRYSTAL GROWTH (ECG) EXPERIMENTS	HALLETT KUGATH
29 JUNE	GE SEMICONDUCTOR DIVISION MICROELECTRONICS CENTER (MEC) RESEARCH TRIANGLE PARK, N.C. MICROELECTRONICS MANUFACTURING PROCESSES	HALLETT KUGATH DR. RUSSELL (MEC)
19,20 JULY	GE MEC, RESEARCH TRIANGLE PARK, N.C: CHIP PRODUCTION LINE INSPECTION & DESIGN CONCEPTS FOR SPACE MICROELECTRONICS MANUFACTURING	HALLETT BIDDISCOMBE DR. RUSSELL (MEC)
26,27 JULY	MRA, INC. HUNTSVILLE, ALA: DESIGN CONCEPTS FOR GaAs INGOT MANUFACTURING IN SPACE	KUGATH LEWANDOWSKI CARIOU

DATES (1984)	LOCATION/SUBJECT	GE ATTENDEES
27 JULY	GE ELECTRONICS LABORATORIES (E-LABS) SCHENECTADY, NY: GaAs VLSI MICROELECTRONICS PRODUCTION LINE EVALUATION (PLSI LAB, MBE LAB)	BIDDISCOMBE BROTHERTON DR. J. HWANG (E-LABS)
31 JULY	GE SSD, VALLEY FORGE, PA. VARIAN VISIT (W. MIRON) VLSI SPACE PRODUCTION EQUIPMENT CONCEPTS	KUGATH BIDDISCOMBE BROTHERTON LEWANDOWSKI
8 AUGUST	GE SSD, VALLEY FORGE, PA. ODETICS VISIT (T.W. KEEGAN) VLSI SPACE PRODUCTION EQUIPMENT CONCEPTS	KUGATH BIDDISCOMBE BROTHERTON FORD
10,11 SEP	SRI, INC. PALO ALTO, CAL. (DR. O. FIRSCHEIN, W. PARK) SPACE STATION FACTORY AUTOMATION ROBITICS/AI APPROACHES	KUGATH BIDDISCOMBE BROTHERTON
10 SEP	PERKIN-ELMER, HAYWARD, CAL. (L. GASIOREK, M. AZAM ALI) E-BEAM DIRECT WRITE TECHNOLOGY & AUTOMATION	KUGATH BIDDISCOMBE BROTHERTON
11 SEP	VARIAN, PALO ALTO, CAL. (M. KEEFER, R. KING) AUTOTRACK & SPUTTERING TECHNOLOGIES & AUTOMATION	KUGATH BIDDISCOMBE BROTHERTON (SRI GUESTS)
11 SEP	APPLIED MATERIALS, SANTA CLARA, CAL. (P. BUTLER, P. THOMAS) ION ETCH TECHNOLOGY & AUTOMATION	BIDDISCOMBE BROTHERTON (SRI GUESTS)
7, 8 NOV	GE/SSD, VALLEY FORGE, PA JPL (R. STAEHLE) DATA SYSTEMS	BIDDISCOMBE BROTHERTON

Figure 1.4-3 GE Working Meetings Summary

2.0 MISSION SELECTION

As mentioned in the study scope Section (1.2) GE's original study plan called for the review of space station remote and manufacturing missions to define a set of generic subtasks. This list of subtasks would be used as a basis to study the applicability of automation concepts.

2.1 CANDIDATE MISSIONS

The first task involved an evaluation of space station missions contained in the "Space Station Mission Requirements Report", May 1984. The report is the output of a NASA wide team whose purpose was to define "....candidate missions and mission requirements and the analysis and integration necessary to validate this definition". The report describes about 100 missions by discipline, i.e., Science And Applications (SAA), Commercial (COM), and Technology Development (TDMX). Also included in the report are time phase mission sets, and estimated resource requirements and allocation. Examples of resources are power, EVA and IVA crew time, volumes, and OMV flights. The one hundred candidate missions were evaluated on the basis of automation potential (i.e., high labor content, EVA requirements, and economic factors) and availability of meaningful data base.

The need for further definition (e.g., operational scenarios, hardware) of candidate missions beyond the Space Station Requirements Report was apparent. To narrow the mission set down by selecting the missions with the best definition, a number of phone calls were made to the various NASA Space Station team members. Suggestions were made by them as to which missions would be best to further evaluate and who to contact within NASA. This together with an assessment of work being done by GE in related areas, resulted in definition of a list of candidate missions. The set, shown in Figure 2.1-1, was presented at the June monthly meeting.

2.2 MANUFACTURING MISSION FOCUS

Most of the missions listed in Figure 2.1-1 had some drawbacks for inclusion in a set of missions for which deeper study would be next addressed according to the original study work plan. For example, the best defined mission would probably be COM 1202 since the commercial process is being currently developed on Shuttle flights. However an in-depth study of the automation aspects would run into proprietary concerns of the Aerospace and pharmaceutical companies presently involved.

Many of the other candidate missions were previous NASA concepts extended for use on the space station platform. While definition of the pre-space station concepts were barely adequate, their use and integration into the space station was, at that point in our study, typically not well defined.

At the suggestion of the NASA technical leaders, GE modified the study plan to concentrate on just two space station manufacturing concepts, but in greater depth. This meant that GE would develop two baseline concepts to define the automation requirements, e.g., robotics, sensor and AI requirements. This would be done in more detail than that in the original work plan, hence would have the advantage of being more specific and realistic.

The two missions selected were based upon the second and the fourth listed in Figure 2.1-1, i.e., Commercial Materials Processing Lab and Microelectronics Chip Production. The primary reason for selecting these two were the availability of expert assistance from Microgravity Research Associates and the GE Microelectronics Center.

CANDIDATE MANUFACTURING/COMMERCIAL APPLICATIONS	NASA REF. NO.*
(1) ELECTROPHORETIC SEPARATION OF BIOLOGICALS (P/U)	COMM 1202
(2) COMMERCIAL MPS PROCESSING LAB (P)	COMM 1201
(3) MERCURY CADMIUM TELLURIDE MATERIAL PRODUCTION (U)	COMM 1208
(4) MICROELECTRONICS CHIP PRODUCTION (U)	--
(5) LARGE STRUCTURE FABRICATION (U)	TDMX 2210 & TDMX 2460

CANDIDATE EXPERIMENTAL MISSIONS	NASA REF. NO.*
(1) EARTH OBSERVATION: STEREOSCOPIC IMAGING SYSTEM (U)	COMM 1019
(2) VEGETABLE/PLANT GROWING CYCLE EXPERIMENTS (P)	SAA 0305
(3) MATERIAL PROCESSING, E.G.	TDMX 2060
- GALLIUM ARSENIDE MATERIAL PROCESSING (U)	
- MERCURY CADMIUM TELLURIDE MATERIAL PROCESSING (P/U)	
- MAGNETOPORESIS SEPARATION (P)	
(4) ASTRONOMY, E.G.	
- SOLAR OPTICAL TELESCOPE (U)	SAA 0003
(5) EARTH SCIENCES, E.G.	
- LIDAR FACILITY	SAA 0201

P = PRESSURIZED MODULE

U = UNPRESSURIZED MODULE

*MISSION NUMBERS ASSIGNED IN NASA SPACE STATION MISSION REQUIREMENTS REPORT, MAY, 1984

Figure 2.1-1 Candidate Missions Evaluated During Study

Design requirements and unconstrained design concepts were developed for the two missions which consisted of defined subsystems, facility layouts, and automation schemes. These were presented at NASA Design Team Meetings (August 22 and October 1) and with helpful comments and direction from NASA, SRI, and the CAL SPACE Automation and Robotics Panel members, a finalization of the design concepts was undertaken.

Data was provided by Microgravity Research Associates (MRA) on the GaAs Electroepitaxial Crystal Growth (ECG) experiment production unit planned for seven STS missions. MRA assisted GE in developing a baseline concept for the GaAs Crystal Production/Wafer Manufacturing Facility for Space Station.

A in-depth analysis of GaAs microelectronics chip production requirements was developed through evaluation of GE Microelectronics Processing Facilities and work with Dr. Keith Russell at the GE Microelectronics Center. The GE Electronics Laboratory in Syracuse, NY also provided data and background information on the GaAs VLSI manufacturing process and the Molecular Beam Epitaxy experimental laboratory.

Manufacturers of microelectronics processing equipment were contacted and asked for support. VARIAN, APPLIED MATERIALS, PERKIN-ELMER, EATON, GCA, ELECTROTECH and HARRIS all provided valuable literature and information on the design and operation of commercial processing equipment and future products. VARIAN visited GE and assisted in the conceptualization of space based processing equipment designs. GE engineers visited three manufacturers in California, PERKIN-ELMER, VARIAN and APPLIED MATERIALS, to obtain further insight into process equipment technology for space application.

2.3 GALLIUM ARSENIDE (GaAs) BACKGROUND

The two missions are related in that the first manufactures GaAs wafers and the second process GaAs wafers into Very Large Scale Integrated Circuits (VLSI's). GaAs devices are just now being introduced as commercial products. There are many advantages of chips made of GaAs over the present silicon based devices. These include: 1) higher switching speed, 2) lower power dissipation, 3) wider temperature tolerance, and 4) better radiation resistance. GaAs can also be used to make better laser devices. Presently, however, high quality GaAs cannot be produced as easily as silicon ingots and is therefore very expensive. The electroepitaxial process for growing bulk crystals in space should be far superior to melt-grown processes. The space produced wafers should have: 1) superior compositional and structural homogeneity, 2) greatly reduced levels of impurities and defects, and 3) striations eliminated.

There are a number of other possible crystal production materials and or techniques that could have been studied. The selection of GaAs was made because of the availability of expert assistance. It is thought reasonable, however, that these specific missions would be representative of the entire class of materials processing in that its automation, robotics, sensors and AI requirements should be quite similar to most other similar missions.

3.0 GaAs ELECTROEPITAXIAL CRYSTAL PRODUCTION AND WAFER MANUFACTURING SPACE MODULE

The conceptual design of a GaAs electroepitaxial crystal growth and wafer production was undertaken under certain assumptions. The design shown here is at an advanced stage in its evolating development cycle. It was configured to fit within the confines of a standard 14 foot diameter Space Station Module. Extensive use of robotics and other automation and mechanization techniques were incorporated into the design to provide nearly total autonomous operation during the growing and slicing operations of the facility. Artificial Intelligence Systems will later have an important role in the operation of this facility, primarily in the areas of troubleshooting, maintenance and process refurbishment.

The process described herein covers the crystal growth, furnace arrangement and processing of the crystal. Ingots produced by the crystal growth will be sliced into wafers and returned to earth with no further processing. A later more advanced design of this facility would polish and complete these wafers in orbit. In this design the seed crystals will be processed for continuous recycling through the furnace. At an earlier stage, the total product, including the seed, could be sent back to earth where the seed crystals would be processed and then returned to orbit. The following paragraphs describe the gallium arsenide production facility as configured for this automation study.

3.1 PROCESS DESCRIPTION

Electroepitaxial crystal growth of Gallium Arsenide polycrystals into high quality ingots, requires a furnace, GaAs source solution, GaAs seed crystals, GaAs source polycrystals and electrical power. Also required is a means to package and

return only the grown GaAs wafers to earth. A cutting (or slicing station) and a seed wafer polishing and cleaning station is required to convert these ingots into wafers.

Figure 3.1-1 is an overview of the concept developed for the facility. A block diagram defining the elements and automation process required for the crystal growth facility is shown in Figure 3.1-2. The elements of the diagram will be described below and the process flow will be evident from the discussion.

3.1.1 GaAs GROWTH PROCESS

The electroepitaxial growth process was developed and patented by Dr. Harry C. Gatos at Massachusetts Institute of Technology (MIT). Microgravity Research Associates, Inc. has an exclusive license for the process. They are presently working on developing the process utilizing the microgravity environment of space. Details of the process need not be described since they are not germane to the automation issues.

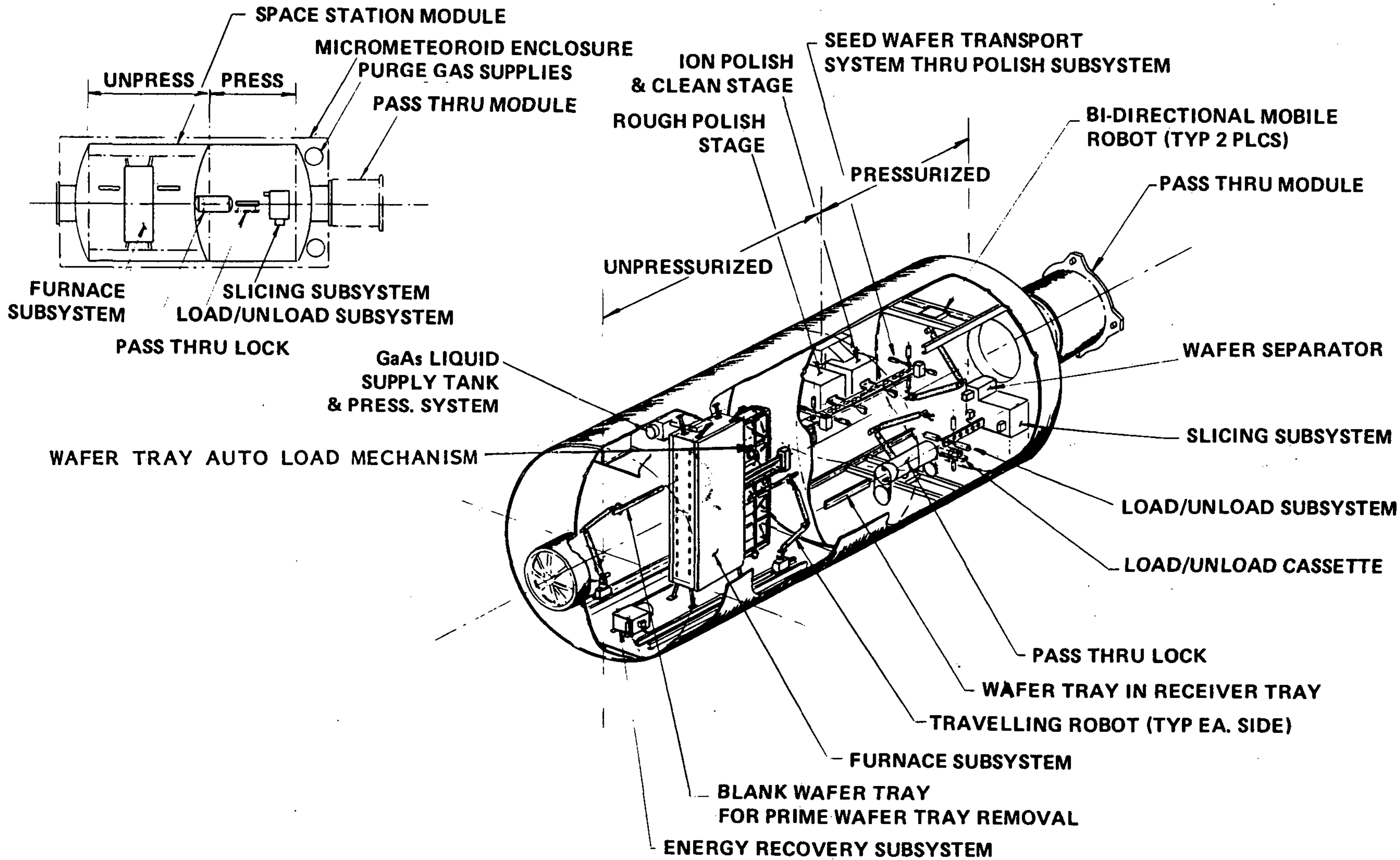

Figure 3.1-1 Crystal Production and Wafer Manufacturing Facility Concept

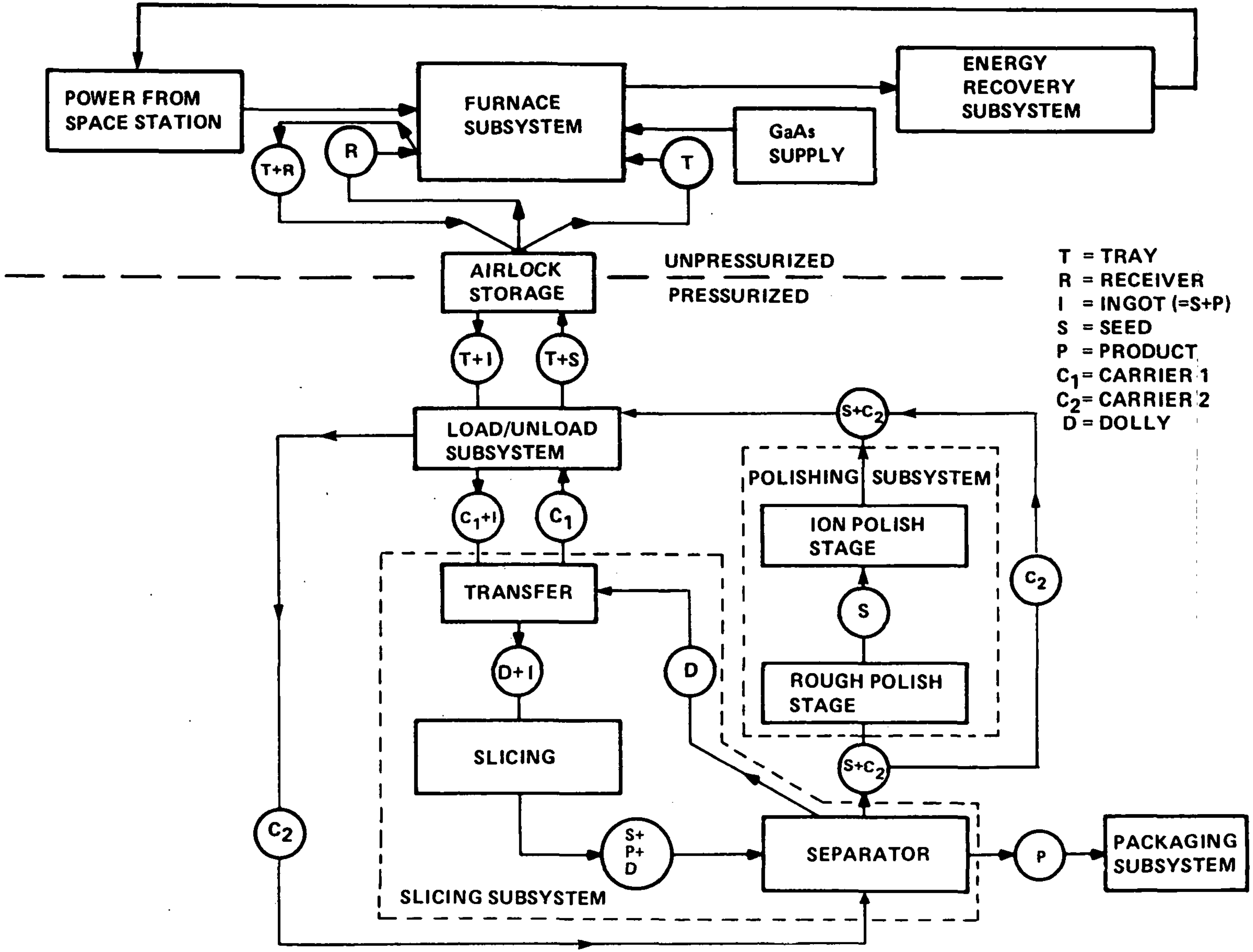

Figure 3.1-2 Crystal Production and Wafer Manufacturing Facility Block Diagram

3.1.2 PROCESS FACILITY

For the space application of epitaxial crystal growth a standard Space Station module will be used to house the furnace and associated ingot cutting and polishing equipment.

The space module will be segregated into two (2) chambers, an unpressurized chamber and a pressurized one. As shown in Figure 3.1-1, the pressurized area will be used for the processing of the ingot into wafers. Pressurizing this area will facilitate the removal of any stray waste material (particles, chips, etc.) from the ingot slicing and polishing stations, by use of a filtered circulation system. An inert gas such as pure nitrogen (N_2) would probably be used to minimize possible oxidation problems.

Material handling of both chambers of the epitaxial growth module will be automated by use of programmed, hybrid robot (1) arms and by automated preprogramming automation techniques. The same hybrid robot arms can also be used to dismantle the furnace, replace source crystals etc., and re-assemble. See Section 3.3.

(1) See definitions in Appendix B

3.2 EQUIPMENT REQUIREMENTS

The processing equipment required for the growing of GaAs ingots and the manufacturing of GaAs wafers will, as noted in Section 3.1, be housed in a modified standard space station module. Modification of this module will require a central pressure bulkhead to separate the space module into two chambers. One of these chambers will house the epitaxial furnace and be unpressurized, and the other house the process equipment for slicing and polishing, and be pressurized.

3.2.1 EQUIPMENT SIZING

The conceptual design of this facility conforms to design requirements which were developed as follows:

The projected demand for GaAs microelectronics of the quality attainable in the space environment was defined. The results are presented in Figure 3.1-1. Microgravity Research Associates (MRA) provided the conservative reference data for this figure based on their own marketing research study. Because of the possibility for development of other materials and/or processes, a saturation of demand is conjectured. If, as MRA predicts, demand increases, a second, upgraded system can be added.

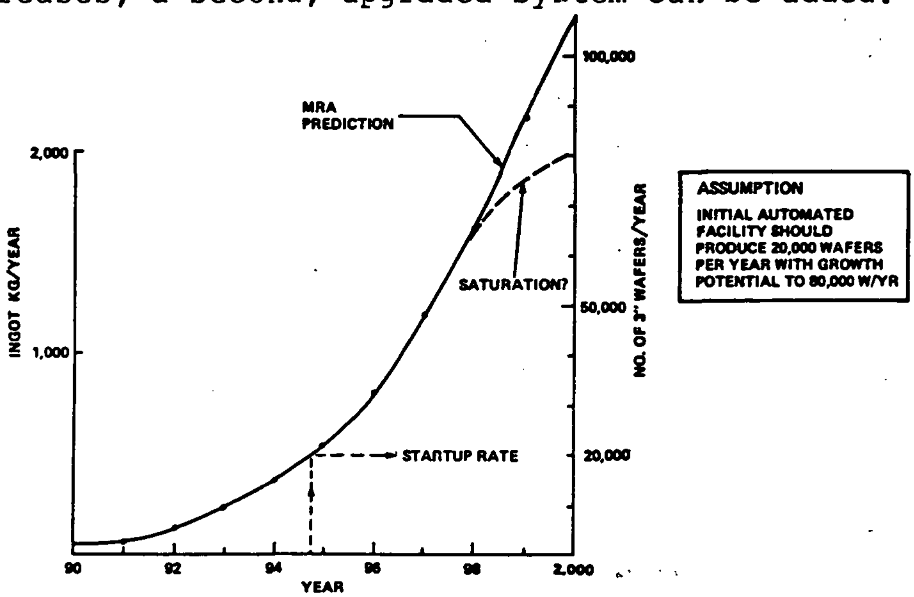

Figure 3.1-1. GaAs Projected Demand

The size of the furnace and size of the ingots to be produced were determined by integrated analyses. An ingot diameter of 3 inches was chosen primarily because furnace power is proportional to area. Five inch diameter ingots are expected to be the earth-based industry norm in the near future, but require nearly three times the power required for producing three inch ingots for the size facility projected. This would be prohibitively high for the IOC space station. Also, because GaAs is extremely fragile, automated handling of three inch wafers will be less risky.

Based on the 3 inch size ingot and the projected demand curve, the furnace was sized at 144 cells. This would meet a startup capacity in the 1995 time frame of 20,000 wafers/year at 26% utilization, and require at peak one third of the available space station power currently planned for the Initial Operational Capability (IOC). Eventual growth to 95% capacity (near continuous operation) would produce 80,000 wafers per year: this would again require at peak roughly one third of the projected space station power available by the year 2000, and an optimization of the automation system into one which is almost fully autonomous, including servicing and maintenance functions.

A power recovery system for the furnace is incorporated in the conceptual design. This should reduce the average power consumption to less than 10% of available space station power. Further study would determine more precisely how much net power would be required. Analyses should also be accomplished to determine if a separate power source would be warranted for each facility, and to determine if other power reducing techniques (i.e., pulsed power) can be effectively employed.

A timeline study determined that each ingot should be grown to a thickness which would yield three wafers per ingot. This is because energy required increases with ingot thickness, the source crystal can be better utilized for this size growth, and adequate time is allowed for tray refurbishment.

3.2.2 UNPRESSURIZED CHAMBER

The unpressurized chamber of the Space Station module will house the furnace unit, tray load/unload mechanism and a dual robot arm system, for tray handling and furnace refurbishment. The chamber vacuum is needed to prevent gaseous contamination of the "sliding" boat furnace concept. It may also be useful in controlling the heat transfer needed to keep the furnace at a constant temperature.

3.2.2.1 Furnace Design Approach

A flat-pack epitaxial crystal growth furnace was selected for this study. To keep the overall voltage drop reasonable, a number of cells are connected in series. Hence the furnace is in reality a number of small furnaces in series. Instead of stacking the individual furnaces along a single axis (or series of 2 or more shorter axes) a flat pack configuration was selected as the only reasonable way to replace the grown product crystals, without disassembly of the entire furnace. The flat pack concept is a variation of the "sliding boat" furnace system described in reference (1).

The flat-pack furnace can be configured in a variety of ways due to the "series" electrical hook up of the growth cells. A packaging study was undertaken and it was found that an arrangement of twenty four (24) trays with six (6) ingots per tray, allowed the minimum furnace and furnace room volume.

Although detailed design of the furnace was not initiated at this time, a concept design was undertaken based on the following requirements:

- o Due the nature of the crystalline growth, a source crystal is required and will need to be replaced after a predetermined number of cycles of the furnace. This will require disassembly of the furnace to install a new GaAs source crystal.

- o To eliminate elaborate holding mechanism for the source crystal and to ensure good electrical conduction through the growth cell, the gallium arsenide (GaAs) solution will be required to be under pressure. This necessitates an external holding tank of GaAs solution and a pressure pump, with supply lines connected to each growth cell.

- o To ensure a very close tolerance on temperature fluctuations, a continual precise thermal control of the furnace will be required. This requires an active coolant loop for the furnace. The coolant should preferably be used in an energy reclaim unit, with the excess used to heat the GaAs holding tank or be dumped to radiator panels on the space station module. Electrical heaters for a preheat cycle of the furnace will also be required.

- o At the end of each growth cycle each ingot tray has to be removed thereby requiring that the GaAs solution pressure be removed from the growth cell so that the ingot tray may be removed without the loss of the GaAs solution. This will require close tolerance fitting of the tray.

All servicing and maintenance of the equipment and processes will be carried out principally by the travelling robots, with manual override by the Space Station Crew. Final backup for servicing can be carried out by either 1) pressurizing the space module and using crew members in "shirt sleeves" type environment, or 2) having the crew use SCUBA type equipment in the pressurized N_2 environment.

Some of the expendables could be stored outside of the module. An access hatch larger than non-rated would facilitate the bulky equipment changeout and upgrading process.

3.2.2.2 Furnace Construction

Due to the electrical current flow through the individual cells and the high temperature requirements of the crystalline growth, an insulative non-reactive high temperature material is needed for the basic furnace construction. Therefore boron nitride, a ceramic, was chosen as the best available material. Boron nitride manufacture is presently limited to 12 X 12 X 12 (inch) blocks, mainly for reasons of limited boron furnace size. Until larger volumes of boron nitride are readily available it is envisioned that the basic furnace will have to be built up from 8 X 8 X 9.5H interlocked blocks, with four (4) cell bores per block. An envelope of sheet alumina is placed around the boron nitride cell block assembly for bearing strength. Thermally insulative standoffs are used to suspend the furnace block assembly between a stainless steel structural housing. Between the steel housing and the alumina shell, heat reflective insulation will be layered to suit a required stainless steel design temperature limit. Further structural insulation will then be added to the outside of the stainless steel housing to limit the overall outside furnace temperature.

Insulative support ties would also be required to suspend the complete furnace between the cylindrical walls of the space station module. The resulting furnace design concept is shown in Figure 3.2-2.

If vibrations or motions of the space station interfere with the crystal growth cycle, it may also be necessary to isolate the entire furnace from the module structure with a compliant type mounting system.

3.2.2.3 Growth Cell

The electroepitaxial growth process requires that a continuous electrical current be passed through a GaAs source puck, through the GaAs liquid solution to the seed growth site (i.e., the liquid GaAs solution/seed crystal interface). The GaAs source puck will be made on earth and supplied to the furnace on an as-required basis. The GaAs solution will be replaced only as required to maintain purity after a finite number of furnace cycles.

A space equivalent to the thickness of slightly more than one ingot is left between the source crystal and the seed crystal; during the growth cycle this space is filled with the pressurized solution of gallium arsenide and then the grown product crystal.

A tray (sliding boat) in which seed wafers have been previously inserted is installed at one end of the growth cell. The tray is also made of boron nitride.

After the crystal growth is complete the tray is removed, the product crystal is removed and the seed crystal and the product sawed off and then processed separately. The seed crystal will then be replaced and reused. See Paragraph 3.2.2.4.

Several options then appear regarding where the seed crystal processing is to be done. To push the initial automation concept we have chosen to do the product separation and seed repolishing in the space station, leaving the product wafer to be returned and processed on earth. In the ultimate growth concept the product wafer will also be polished and processed totally in space. Product polishing is very little different from the seed polishing and hence there seemed to be no reason to study this ultimate concept at this time.

3.2.2.4 Seed Wafer

The seed wafer, upon which the GaAs ingots are grown, is made of pure gallium arsenide crystal. The growth surface of the seed wafer must be highly polished prior to the growth cycle. This will be accomplished in the polish and clean station on the pressurized chamber of the process module. See Paragraph 3.2.2.3.

3.2.2.5 Ingot Tray Installation

As noted in 3.2.2.1, the minimum furnace envelope is one in which there are twenty four ingot trays with six ingot stations per tray. These trays have to be (1) loaded with new seed wafers, (2) inserted into the furnace, and (3) removed after growth of new ingots of GaAs.

Initial concepts of the "sliding boat" tray furnace method evolved around a robot tray load/unload system. However, due to the expected high forces (100-200 pounds) needed to insert a tray into the furnace by robot arm, and the precise alignments required, an injection type tray auto load system was later conceived. The resulting design is shown in Figure 3.2-2.

The new tray, loaded with seed crystals,is inserted into the furnace port on the far side, and serves to (a) push the ingot tray out and (b) minimize the amount of GaAs solution spilled from the growth cells. To further reduce any spillage of the GaAs solution, a receiver tray was conceived such that the ingot tray, upon being pushed out of the furnace, will automatically slide into this receiver tray. This concept is shown in Figure 3.2-3.

This auto load system will attach and be accurately aligned with the tray openings, to one side of the furnace. A structural frame will support a dual ejector system one per side for the two runs of tray positions in the furnace arrangement. It will also support an actuator each side for insulation plug removal from the furnace face.

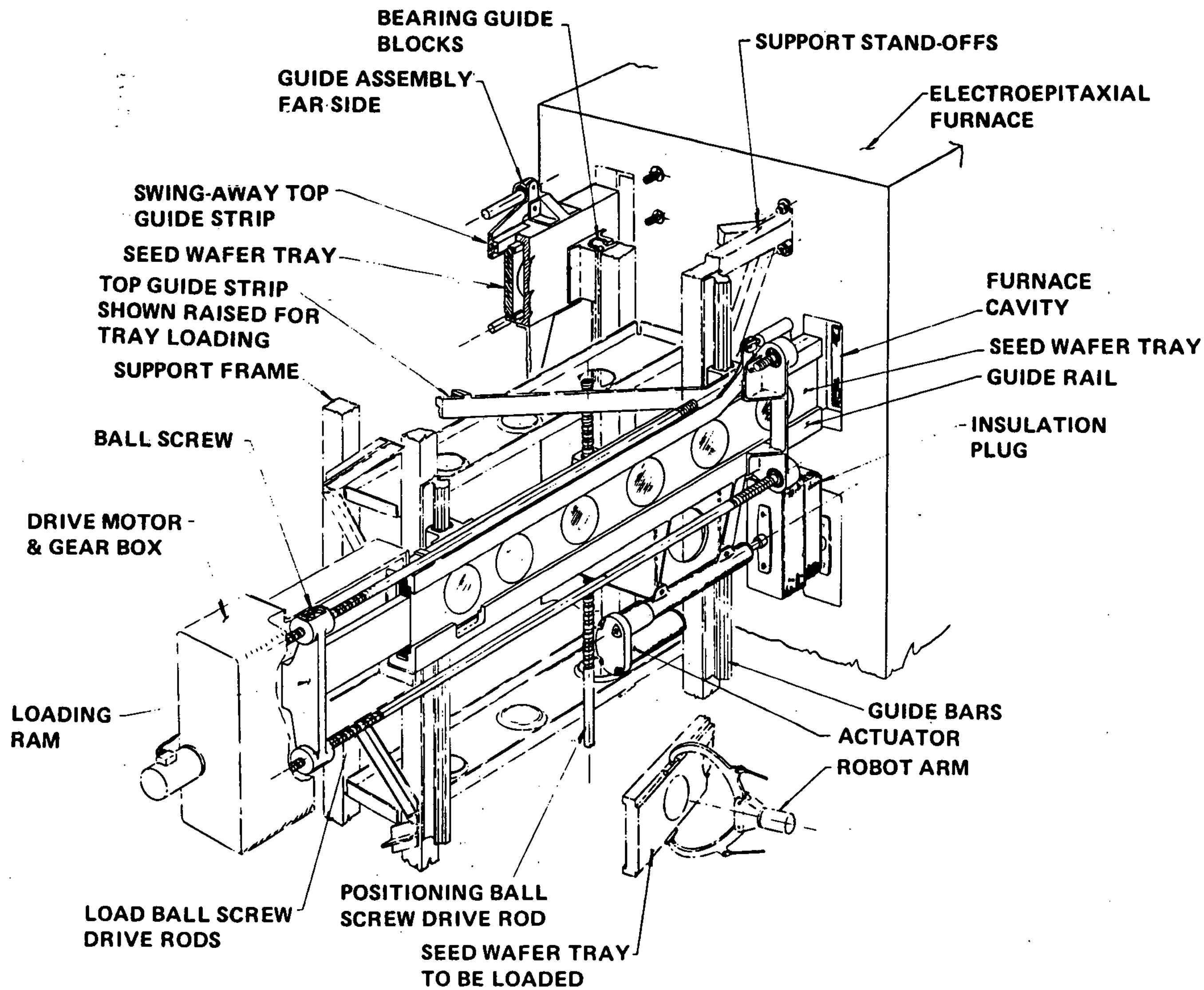

Figure 3.2-2 GaAs Furnace Wafer Tray Auto Load

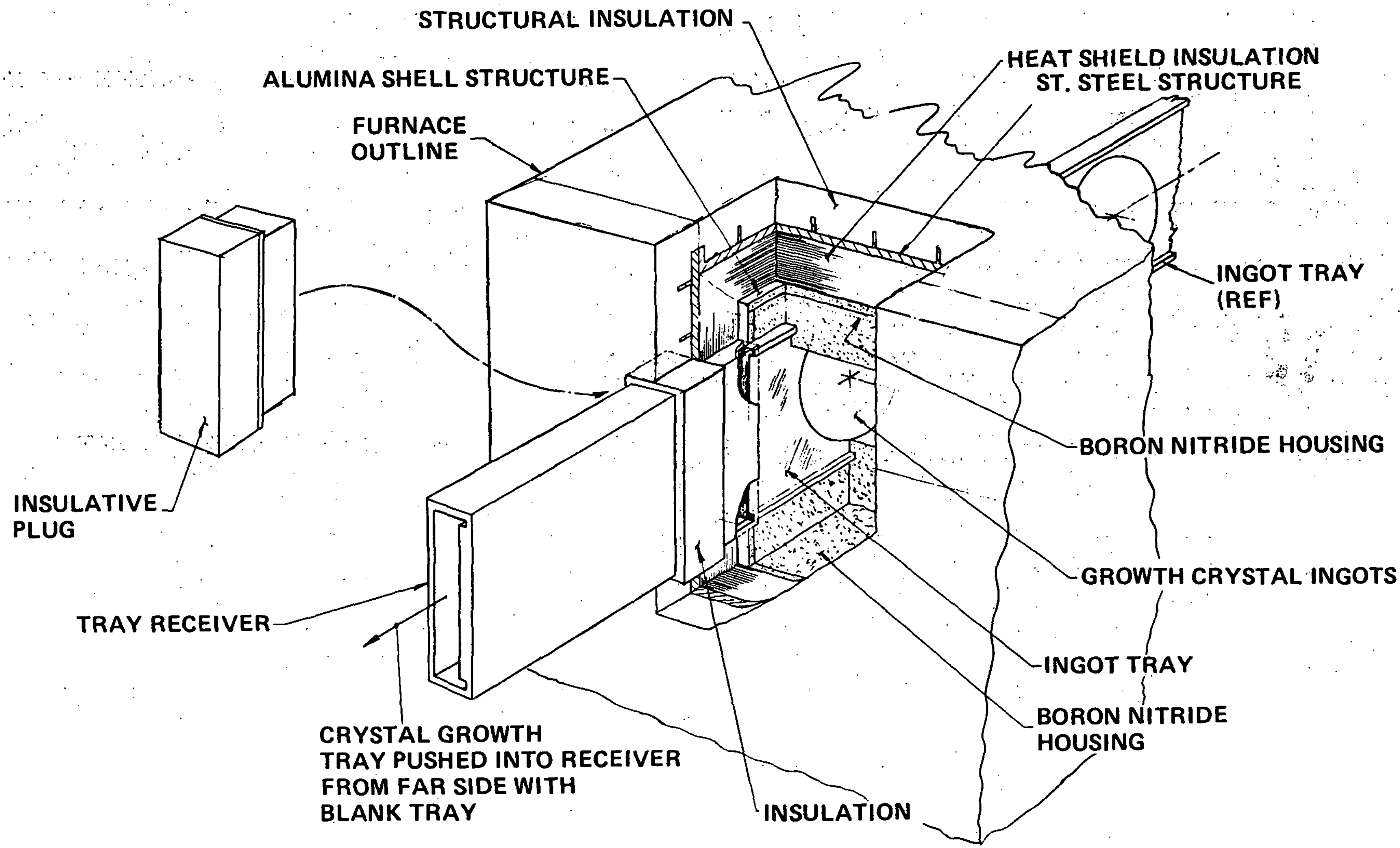

Figure 3.2-3 Automated Receiver Tray Mating With Crystal Growth Furnace

Vertical guide tracks attached to the frame will allow the ejector guide to be positioned opposite any desired furnace tray slot. This will be accomplished by a single ball screw jack system. Ahead of the tray ejector guide, an insulation plug removal actuator will be positioned to remove the insulation plug from the furnace wall. This will be a simple push-pull system with a quick release ball detente system for attaching onto the insulation receiver socket.

After removal of the insulation plug, the ejector guide track will be moved into position opposite the tray opening.

Trays of freshly loaded seed wafers will then be positioned for loading into the ejector, by the robot arms. A mechanism will pivot the top guide rail of the ejector track. The robot arm will insert the loaded tray into the guide track and the pivoted guide rail will return to the guide position capturing the ingot tray in the track system.

A loading ram is now ready to insert the newly loaded seed wafer tray into the furnace. The ram will be driven by a pair of ball screw jacks driven from a common gear box and drive motor.

A receiver tray can now be positioned on the far side of the furnace to receive the fully grown ingot tray from the furnace. This, it is felt, can be adequately carried out by the robot arm system.

On removal from the furnace the receiver tray, complete with ingot tray, is transported to a temporary storage area and then it's passed through an airlock port between the pressurized and unpressurized chambers of the space station module. The receiver tray is configured to reduce the cool down rate of the growth ingots.

3.2.2.6 Furnace Operation

For electroepitaxial growth of the GaAs ingots, a constant temperature must be maintained throughout the growth cycle.

For this study it was determined (Section 3.2.1) that the thickness of GaAs equivalent to three (3) wafer slices would be grown per growth cell in the normal growth cycle. Figure 3.2-4 shows the actual crystalline growth allowance per ingot.

	INS	MM
#1 WAFER	.025	.635
SAW CUT	.015	.381
#2 WAFER	.025	.635
SAW CUT	.015	.381
#3 WAFER	.025	.635
SAW CUT	.015	.381
SEED WAFER POLISH ALLOW.	.004	.100
BASIC SEED WAFER	.006	.152
	.130	3.300
INGOT THICKNESS		

Figure 3.2-4 Ingot Thickness Determination

The temperature throughout the entire growth cycle is a parameter which must be closely controlled. To accomplish this performance an active temperature control system must be incorporated into the furnace design.

For cooling, a coolant such as freon could be pumped through a labyrinth of cooling channels, similar to the water jacket in a reciprocating engine.

Prior to initiating power for the start of growth cycle, the furnace must be brought up to operating temperature by resistance heating coils (elements) placed throughout the furnace. It is proposed that waste heat from the furnace block should not be wasted, but rather should be converted back into useful electrical energy by use of a thermoelectric generator, and also later it may be used to supply heat to various subsequent process in the GaAs chip production module.

3.2.3 PRESSURIZED CHAMBER

The pressurized chamber of the space station module will house the slicing and polishing units of the epitaxial crystal growth system facilities. The design concept for the pressurized chamber is shown in Figure 3.2-5.

Due to the mechanical nature of these operations, GaAs dust will be created in this area. It is therefore recommended that this chamber be pressurized to around 2 P.S.I, and that a gas flow management conditioning and filtering system be installed in this pressurized chamber. The module should be designed for an increased pressure of around 10 P.S.I. at which time crew members could enter, for general repairs or troubleshooting.

On leaving the furnace area, trays of grown ingots will be passed through a pressure lock to the load/unload station where the ingots will be removed from the trays and placed into cassettes for handling and transporting to the various slicing and polishing stations, a design concept for which is presented in Figure 3.2-6.

Cassettes of ingots would then be handled by mobile robot arms for passing from station to station. An auto-track system could also be used for the cassette handling. However, since robot arms will be required for routine maintenance and general repair and part replacement it seems reasonable to use these arms for cassette handling.

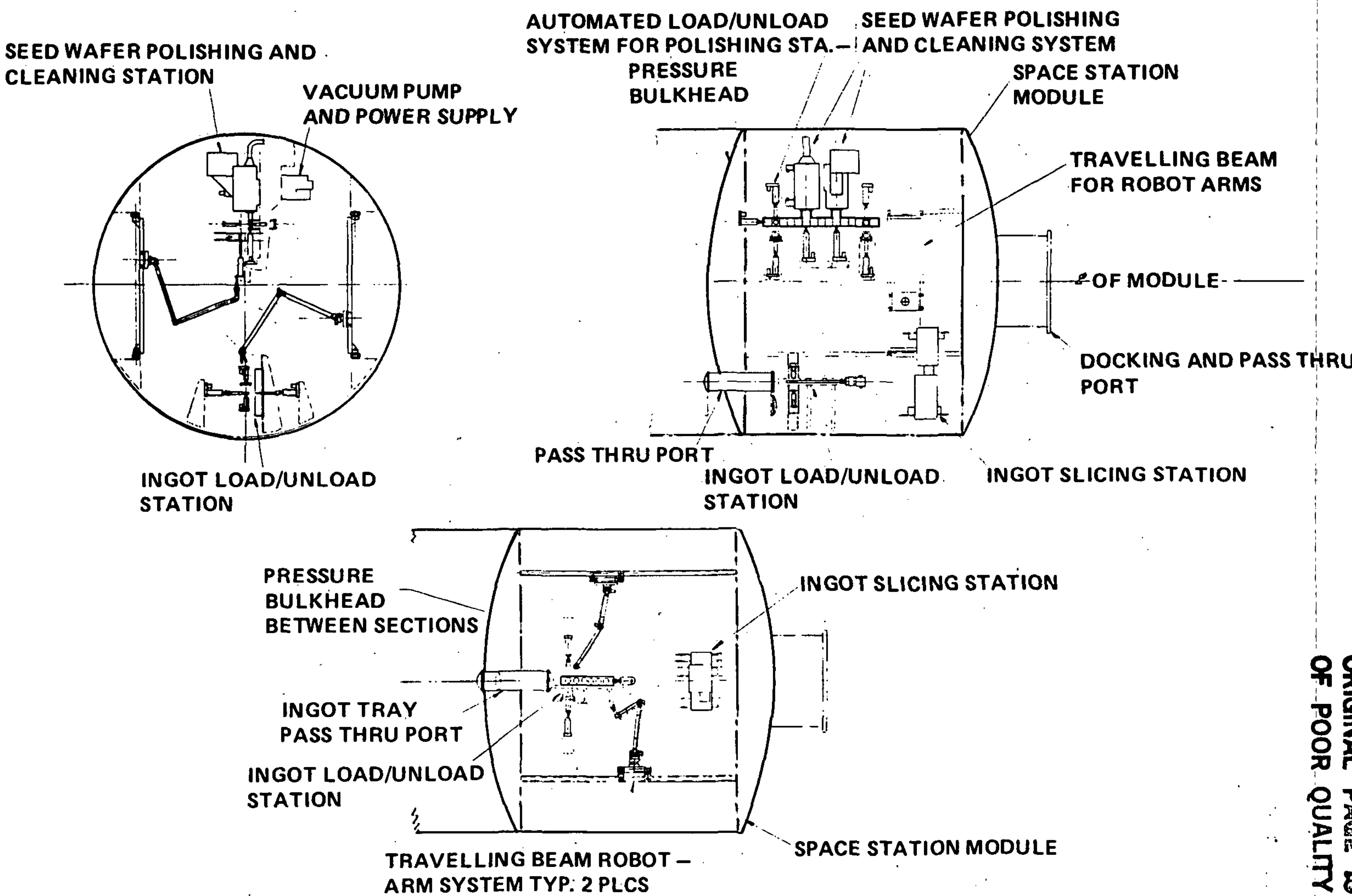

Figure 3.2-5 Wafer Manufacturing Facility

Pressurized Chamber

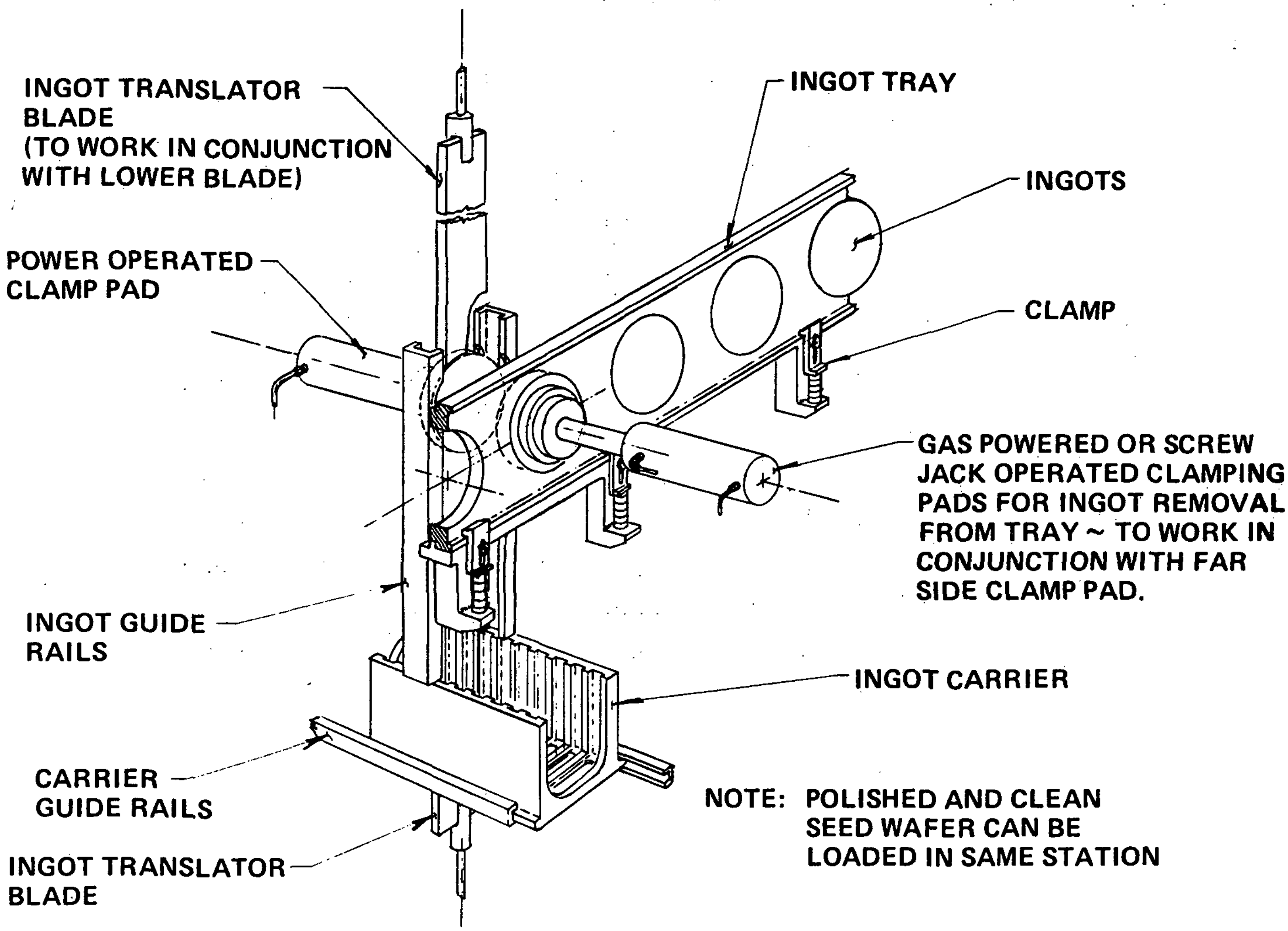

Figure 3.2-6 Automated Ingot Unload From Tray

The ingots are sliced, forming 3 product wafers and the seed crystal. They are then routed in two directions: (1) the rough product GaAs wafers are loaded into containers for eventual shipment back to earth (or in the more advanced conceptual design to the wafer chip processing module) and (2) the seed crystal wafer puck is sent to the polishing and cleaning stations prior to being loaded back into the ingot trays for a new ingot growth cycle.

3.2.3.1 Load/Unload Subsystem

The load/unload station is situated adjacent to the pass through port. The ingot and receiver tray combination when removed from the furnace are placed into the pass through port. Pressurizing of the port is carried out and the door is automatically opened on the pressure side of the space module. An automatic translator arm is then stroked into the chamber and locks into the ingot tray and proceeds to remove it from the receiver tray while it is still in the pass through port. The receiver tray never leaves the pass through port on this side. The ingot tray is pulled intermittently along the load/unload station bed. Automatic clamping by 'muscle' clamps is instituted during load & unload cycling. When the ingot is on-station, two piston arms are stroked up to the ingot from both sides at right angles to the ingot tray. Pressure sensing heads allow only the minimal required amount of clamping force on the fragile ingot to be applied. On locating the ingot puck, both pistons are stroked in one direction to force the ingot from the holding tray, and over to the cassette load position. At this position two other translator blades are stroked to make contact with the edges of the ingot; again pressure sensing heads are used to avoid unnecessary pressure on the ingot. Upon contact of the blades, the first two pistons release, and the translator blades are stroked in a single direction to place the ingot into the "on station" cassette.

Two pistons and blades are needed to captivate the ingot owing to the lack of gravitational forces. Alternately an electro-static arm could be looked at to achieve this cassette loading operation.

The reverse procedure would be used to unload the polished seed wafer from its cassette and insert it into the ingot tray. The total time required to unload and load one ingot by this method is estimated at approximately 40 seconds. Assuming 10 second for pass through port pressurizing & unpressurizing cycles and 60 seconds for tray removal & tray loading cycles, the total time for a complete loading and unloading of the 24 trays and 144 ingots from the furnace would be approximately 2.6 hours.

3.2.3.2 Slicing Subsystem

Cassettes would handle one complete tray, i.e., 6 ingots. After the cassette is loaded at the load station it would be robotically transferred to the slicing station and loaded into the cassette handling part of this station.

The slicing station takes the grown ingot and, by diamond wire cutting, slices the three wafers from the ingot, leaving the seed wafer and graphite puck to be recycled. The general arrangement of the slicing station is shown in Figure 3.2-7.

Cassettes would be sequenced through the station using standard industrial procedures for cassette handling. After the ingot is stationed in the correct position, the sequence is as follows: a receiver cup strokes into place over the positioned ingot, a translator blade then strokes through the base of the cassette and deposits the ingot into the receiver, the receiver then strokes down carrying the ingot into a tracked dolly that has been positioned to receive the ingot. Upon positioning of the ingot into the dolly, a mechanical socket wrench is automatically moved into position to tighten the clamp pad on the dolly, locating the graphite base of the ingot up to the registration face of the dolly. The receiver cup is removed and the dolly is moved along the track to the slice position. On arrival, a

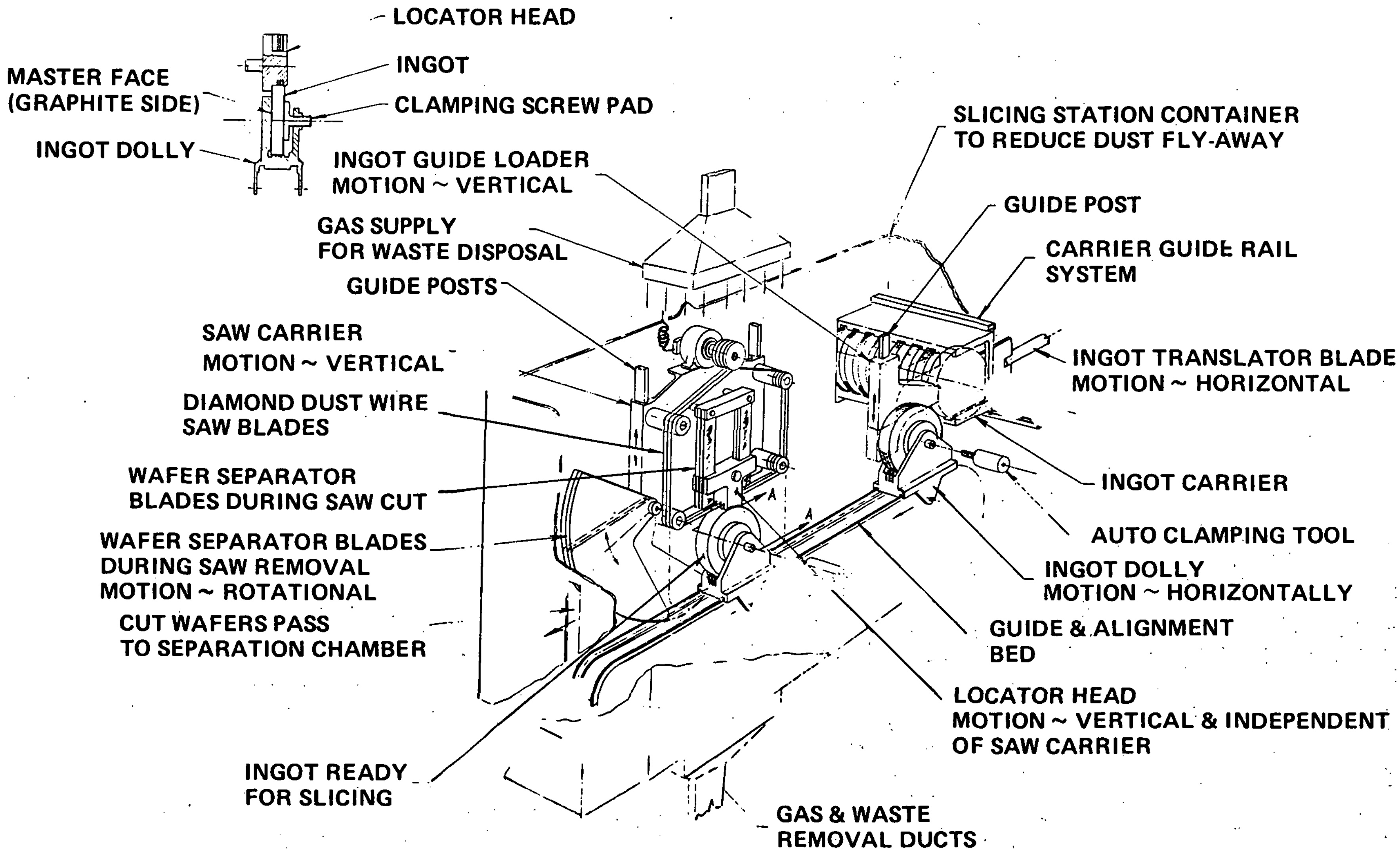

Figure 3.2-7 Automated Raw Ingot Slicing Station

locator head is moved down onto the top of the ingot and again registers off the graphite base of the ingot, this in turn sets the three wire saws in the correct position for cutting. With the locator block now retaining the sliced sections until after the full cuts have been carried out, the holding clamp on the dolly can now be released.

The diamond wire saw blades are started and with the three cuts occurring simultaneously, a controlled rate cut is made across the full diameter of the ingot. During sawing and retrieval of the wire saw blades after cutting, separator disk sections are positioned between the sawn wafer sections. After removal of the cutting unit, the dolly is moved along the track to a port hole which allows the three sliced sections and the seed puck section to partially appear through this window. Pressure sensitive tweezers or electro-static head arms will then pick the sliced wafer sections one by one from the port hole and deposit them into a can (similar to tube packaged potato chips) with separator pads positioned between each wafer section, for subsequent return to earth. The seed wafer puck is also removed and loaded into another handling cassette for transfer to the polishing and cleaning stations.

The slicing operation is carried out dry and all operations are contained within a housing. A separate supply of filtered gas is passed through this housing to carry away all cutting debris with it. An electro-static plate may also be positioned inside the housing for particle attraction. This plate would have to be cleaned off periodically, e.g., during the two month planned process station refurbishment.

3.2.2.3 Polishing & Cleaning Stations

A rough and final polish has been assumed to be required to prepare the seed wafer growth surface for new crystal growth. For the space station application it has also been assumed that a completely dry process system would be best for these two steps. This will avoid the zero "G" handling problems attendant with the use of conventional wet polishing methods.

The Polishing Subsystem design concept is presented in Figure 3.2-8. Roughly cut seed wafer pucks previously loaded into cassettes at the slicing station will be transferred by robot arm to the start of the polish station track. Seed wafer pucks will be unloaded from these cassettes by a system of transfer arms and pistons, similar to that described for the load/unload station. The pucks will be loaded onto individual transfer pallets for transfer to and from the polishing stations. These pallets will be designed to hold the seed wafer puck securely and accurately during the process steps. The pallets will be retained at all times on a fixed loop type track that will transfer the seed wafer pucks from station to station and onto the cassette reload station for transfer of the finally polished seed wafer back to the tray load station for recycle to the crystal growth furnace. Unload pallets will then return to the start of the loop via elevators and a lower powered track system.

On arrival of the pallets at the various polishing stations, an extendable roll-up boom will engage the pallet and transfer the pallet from the track into the receiver port inside the polishing station. The pallet will be designed such that a vacuum can be pulled across the puck-to-pallet interface for accurate positioning and holding and the pallet-to-station interface, for further accurate positioning and holding of the pallet.

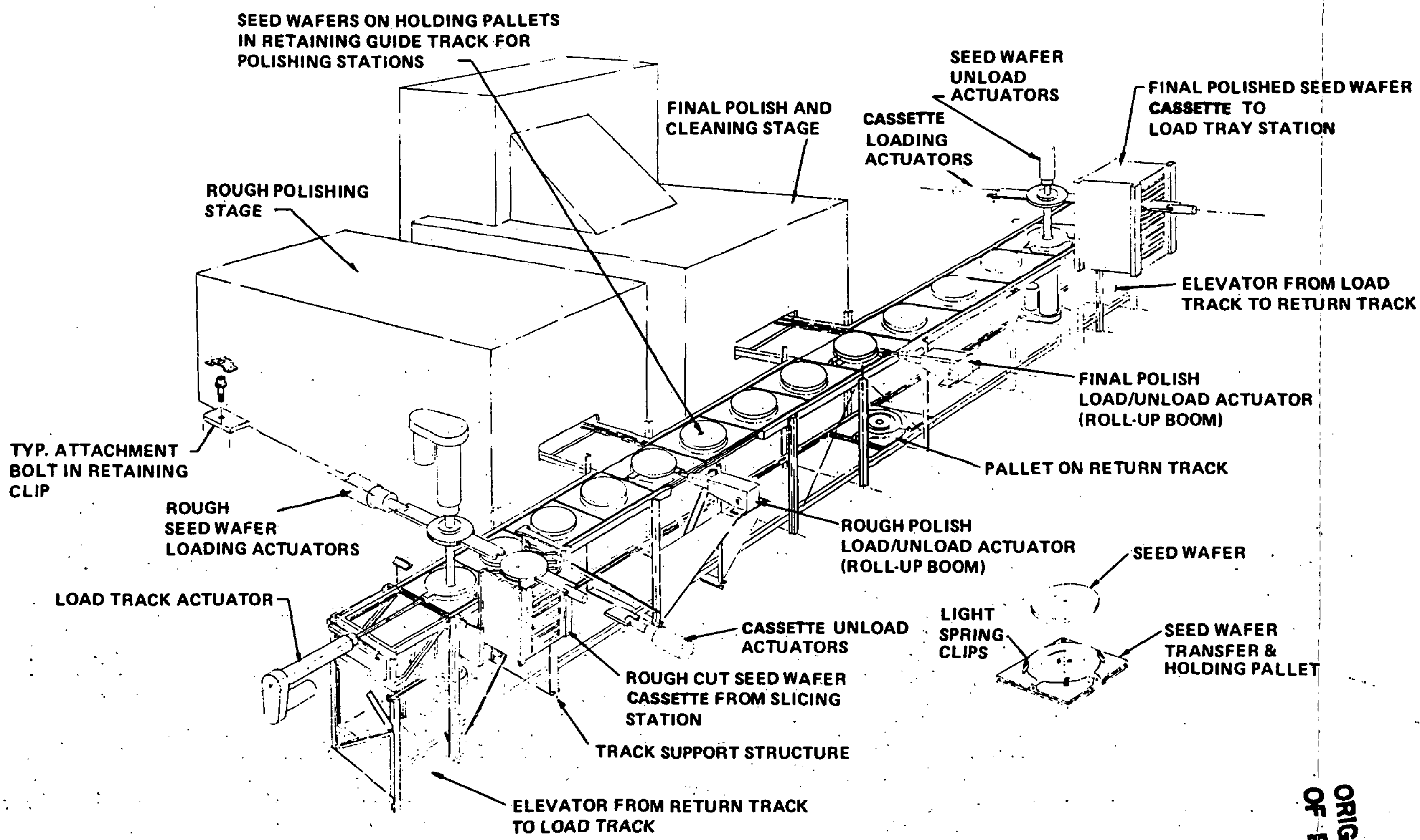

Figure 3.2-8 Seed Wafer - Polishing Subsystem

Depth and alignment sensors for proper seed wafer orientation and also sensors for checking the final surface finish, will be required as part of the polish/cleaning stations.

The rough polishing station is similar in design to that of a horizontal grinder, polishing the surface from approximately 32-64 micron initial finish as cut to about 8-12 micron finish.

The final surface finishing station is a low energy sputter-etching or ion-polishing system, which will not only polish the complete seed wafer puck to at least a 2-4 micron finish, but will also serve to remove any debris or other contamination from the surface.

The individual stations will be self-contained and modularized in their own housing including a dedicated gas filtered management system. Connections of power and signal, and mechanical placement will be designed for robotic actuation so that the complete module can be replaced.

3.2.4 MAINTENANCE

Monitoring sensors will be positioned at all critical points throughout the entire GaAs ingot production system, in order to maintain an uninterrupted flow of "good" wafers. All individual units will be accessible for robotic replacement of the affected component in the case of a system failure. Certain areas inside the process units (for example the diamond saw cutting head) will be made accessible for periodic replacement using a robot arm. An overall scanning camera system should be installed for periodic visual checking, by crew members. This camera system would also be coupled to the master computer in order to detect via a preprogrammed room images any misplaced or broken wafers.

At the end of a predetermined number of growth cycles (as dictated by the initial source crystal overall length used) the furnace must be dismantled for source crystal replacement and, due to the anticipated losses during each growth cycle, the GaAs solution will also need replenishing.

With the present configuration, it is envisioned that, approximately every two months, a complete overhaul and general cleaning of the space module will be necessary.

Furnace refurbishment will be a fairly complex procedure, but it is assumed that all dismantling and refurbishment operations entailed in this overall procedure will be carried out by means of programmed robots, with appropriate manual override provisions to permit crew member intervention at any critical stages.

Robot intervention in the form of assembly-disassembly will have to be taken into consideration on final furnace material selection and overall design configuration.

3.3 AUTOMATION CONCEPT ASSESSMENT

Our assessment of the automation concepts presented above comes from three sources: 1) the general background of the GE study team members and the GE Corporate consultants, 2) discussions of the concepts at the monthly status meetings by various people from NASA, other contractors, the CAL SPACE panel, and SRI, and 3) specific comments from SRI personnel as a result of our meeting at Menlo Park, CA on Sept. 10th.

The automation requirements for the GaAs electroepitaxial crystal growth manufacturing system are summarized in Figure 3.3-1. They are broken down into three areas, process mechanization, robotics, and artificial intelligence (AI). Sensors are not considered separately as no specific requirements

	AUTOMATION FUNCTIONS	SPACE AUTOMATION TECHNOLOGY ASSESSMENT
ROBOTICS	FURNACE ROOM TELEOPERATOR/ROBOT __Process Transport__ o Furnace Load/Unload - Move and align blank trays for unload. - Move and align receiver tray for load/unload. o Tray/Receiver Transporter - Move tray and receiver from furnace to airlock. - Place tray/receiver in airlock fixture. - Return from airlock to furnace with tray/receiver combination.	These robotic functions are SOA for terrestrial applications, but have not been fully developed and tested in space.
	__Maintenance__ o Furnace Disassembly - Disassemble furnace to replace source crystal. - Reassemble furnace.	The difficulty of doing this subtask depends on how much the furnace design can accommodate remote disassembly "tricks of the trade." Maintenance functions will initially require teleoperation but will evolve into an adaptive robot operation.
	SLICE/POLISH ROOM TELEOPERATOR/ROBOT __Process Transport__ o Load/Unload Station - Transfer cassette from load/unload STA to slice STA. - Transfer cassette from polish/clean STA to load station. o Slicing Station - Transfer cassette from slice station to shipping STA. - Transfer cassette from slice STA to polish STA.	Same comments as above for robotic material handling.
	__Maintenance__ o Maintenance and Repair - Remove and replace all actuators and mechanisms. - Remove and replace all process subsystems. - Remove and replace all process units as required.	These replacement functions should be easily accomplished as no tight dimensions are needed when modules are replaced. Teleoperation during initial operation will evolve into higher level robotics with time and experience.
ARTIFICIAL INTELLIGENCE	PROCESS CONTROLLER o Monitor and Control Furnace Power and Temperature o Coordinate Overall Material Process Control o Monitor and Control Process Station Equipment	The process controller has close terrestrial applications for its monitor and control functions. Addition of a knowledge base would aid development of a fully autonomous controller.
	EXPERT MAINTENANCE CONTROLLER o Monitor and Flag Abnormal Operation of Equipment o Insulate Equipment Faults, Trouble Shoot, and Develop Best Course of Action	The maintenance AI expert system will need development but terrestrial parallels should exist.

	AUTOMATION FUNCTIONS	SPACE AUTOMATION TECHNOLOGY ASSESSMENT
PROCESS MECHANIZATION	FURNACE ROOM o No Automation - Except Furnace Load/Unload Mechanisms Could Be Automated Instead of Robotic o Monitor Temperature, Time and Power Fluctuations o Record Number of Cycles for Refurbishment Time. SLICE/POLISH ROOM o Slice/Polish Room Load/Unload Station - Remove Tray from Receiver and Airlock - Positions at Load/Unload Port - Remove Ingot from Tray - Place in Cassette - Remove Polished Seed Wafer From Cassette o Slicing Station - Remove Ingot from Tray - Place in Slicing Dolly. - Transfer ingot to saw and then to separator. - Remove sliced wafers from separation - place in storage can. - Remove sliced seed wafer pick from separator - place in cassette. o Polish/Clean Station - Remove seed puck from cassette - place in pallet. - Move pallet along service track. - Move pallet in and out of polish and cleaning station. - Position pallet for correct alignment in polish and clean station. - Remove polished seed wafer from pallet - place in cassette. o Airlock - Open end doors - fill or evacuate airlock. - Hold and Release receiver tray. o General - Monitor wafer and station temperatures. - Monitor cleanliness and pressure.	All the mechanisms and controls have terrestrial counterparts, and except for space qualifications can be classified as SOA.

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Figure 3.3-1 Crystal Production and Wafer Manufacturing Facility Automation Requirements Summary

for advanced sensors were found. This was more from lack of time to study this area rather than a identified lack of need for advanced sensors.

It is our opinion that for this concept automation in the form of process mechanization and robot material handling is well within the realm of feasibility for the time period assumed. Design of the basic automation system should not of itself create much of a design challenge. However designing for long life, fault tolerant unattended operation, self-repair and maintenance, computer coupling, and the development of an AI system for the hybrid robot will require a fairly extensive development program. The AI system as proposed here will require the greatest advance in the SOA. Such advances as discussed below seem quite necessary so that such manufacturing concepts as proposed herein can indeed be economically viable.

3.3.1 PROCESS MECHANIZATION

Much of the automation, as can be seen from Figure 3.3-1, is in the form of processed mechanization hardware, similar to that used in terrestrial factories of today for the handling of materials and equipment. However, much rethinking of the mechanization system will have to take place to lighten, sensitize and redesign for vacuum zero "G" environment.

Many mechanisms have been designed by GE and others for space application, but these mechanisms usually take the form of "one shot" designs, for example, solar array or antenna deployments, or for limited life applications, e.g., the space Shuttle remote manipulator system. Long life continuous working mechanism have rarely been required for space applications.

Dry lubricants will be required for all moving parts, however studies will have to be undertaken as in the area of long life space wear on dry lubricants for rotating and sliding surfaces. Self diagnostics will be required for breakdown and troubleshooting avoidance.

Designs will have to be modular and interfaces simple and clean to facilitate robot repair and replacement. A line of modular components may have to be developed, to simplify the spares requirement, and common mechanical and electrical interfaces must be developed even at the expense of over design.

Much of the mechanization proposed for the crystal growth manufacturing facility is standard and state-of-the-art, and perhaps seems overly designed or complicated when considering it is only dealing with the handling of a single .025 inch thick wafer or a .25 inch thick seed puck. However, the process mechanization must now contend with zero-g, i.e., the floating object problem and cannot use gravity for its benefit as often done on earth. Further work should be done to eliminate much of the dual function mechanisms and substitute designs such as an electro-static pickup arm or magnetic levitation systems for the handling these single fragile wafers in the zero "G" space environment.

Between the process mechanization and the four robots described below, a large number of motor/gear boxes actuators are required. Substitution of yet to be developed simple and reliable "muscle" units, i.e., electrically charged tendons as actuators should be encouraged for application into the Space Station Automation System for reliability and packaging reasons.

3.3.2 ROBOTICS

Two independent robot systems have been identified for the crystal growth manufacturing facility. One system in the unpressurized chamber, servicing the furnace handling ingot trays, and the other in the pressurized chamber handling the cassettes for the finished product. The robot systems are conjectured to be a hybrid system. By that we mean normally the robots carries out its routine preprogrammed tasks. But in certain circumstances they could be used as teleoperated manipulators. As explained by Park of SRI (2):

> "The equipment in the facility should be operable remotely from the laboratory module or from the ground, and the outputs from the various sensors should be available to the operators. In the case of the robot arms and cameras this provides a kind of telepresence which will be extremely useful for the following purposes:
>
> - As a backup mode of operation while automatic equipment is repaired.
> - To reduce the need to send people into the facility to take care of problems that cannot be handled completely automatically.
> - To provide rapid access or an alternative means of access to a manufacturing area in an emergency, without having to put on SCUBA gear or a space suit and get through an air lock. Also, the lock doors could be blocked or jammed, and the area could be hazardous.
> - To move the arms through a sequence of positions during procedural programming ("training") of the robots for a task.
> - To experiment with new tooling or procedures in their process of extending the automatic capabilities of the system.
>
> Telepresence would probably be used at first to perform repairs and the more difficult preventive maintenance procedures. As the automation capabilities evolve, more maintenance and later the minor and finally major repairs would be done automatically. Ultimately, telepresence would be used only in emergencies. No matter how automated the system becomes, however, the telepresence capability will always be a desirable safety factor."

(2) Space Based Fab of GaAs integrated circuits by William T. Park, SRI International, September 1984.

Most of the material handled is relatively light and no need was found for extreme speed with the long furnace cycle time. The primary or first function of the robot is to service the crystal growth manufacturing system. The robot will be required to handle the ingot trays both "in" and "out" of the furnace and the cassettes "to" and "from" the processing systems. Both these tasks are predetermined and programmable to the point of total automation.

The secondary functions of the robot arms is to service the crystal growth overall equipment, replace warn parts, unclog a clogged mechanization sequence, recapture a stray wafer, tray or cassette, and do general housekeeping updates and supply replacements.

Thirdly the functions of the robot arms are to do major dismantling of furnace equipment or process equipment for repairs or refurbishment. It is this function that the greatest challenge lies, more in the AI control required than in the robot's mechanical design.

In both areas of the crystal growth facility the robot manipulator arms are shown on travelling cars for what seems to give adequate freedom and access to all parts of the manufacturing chambers. This is a simpler concept than a walking or free flying transport system.

Zero gravity will allow the robot arms to be lighter than conventional industrial systems. Flexibility in the arm and control mechanism can create difficult control and operating feed back characteristics. This is especially true if the arm is handling large masses at unreasonable velocities. However this does not appear to be a major problem in this concept.

Robots will require fully developed interpretive, adaptive, and generative control techniques.

Some of the Interpretive Signals are as follows:

- o Interpretation of forces at grippers to determine grasp, object, mass, etc.
- o Use of visual and tactile signals for use of recognizing location and inspection.
- o Methods for detecting jamming & wedging when putting parts together.
- o Method for building geometric models from sensory information.

Typical adaptive signals are:

- o Automatic calibration methods for visual and tactile sensors.
- o Integration of visual and tactile feedback in fitting and fastening operations.
- o Sensor-based collision avoidance methods for mechanism control.

Required generative signals are:

- o Coordination of multiple articulated mechanisms for collision avoidance.
- o Handling of limp materials.

The key to the capability of the robot system is the design of versatile end effectors. The robot will need several styles to cover the various tasks. A typical cassette gripper is shown in Figure 3.3-2. Using the same robot arm a typical maintenance head is shown in Figure 3.3-3. Interchanging the end effectors is, of course, an old, tried and proven concept for hot-lab manipulators. Recent developments in robots indicate changeable end effectors with breakaway force/torque limiters, signal, and power (electrical, hydraulic or pneumatic) transfer across the interface will soon be widely available. The competing technology concept for an end effector is to use a multi-finger hand with prehensile grip and the use of standard tools. For our structured manufacturing environment, however, we feel the interchangable end effector concept better suited.

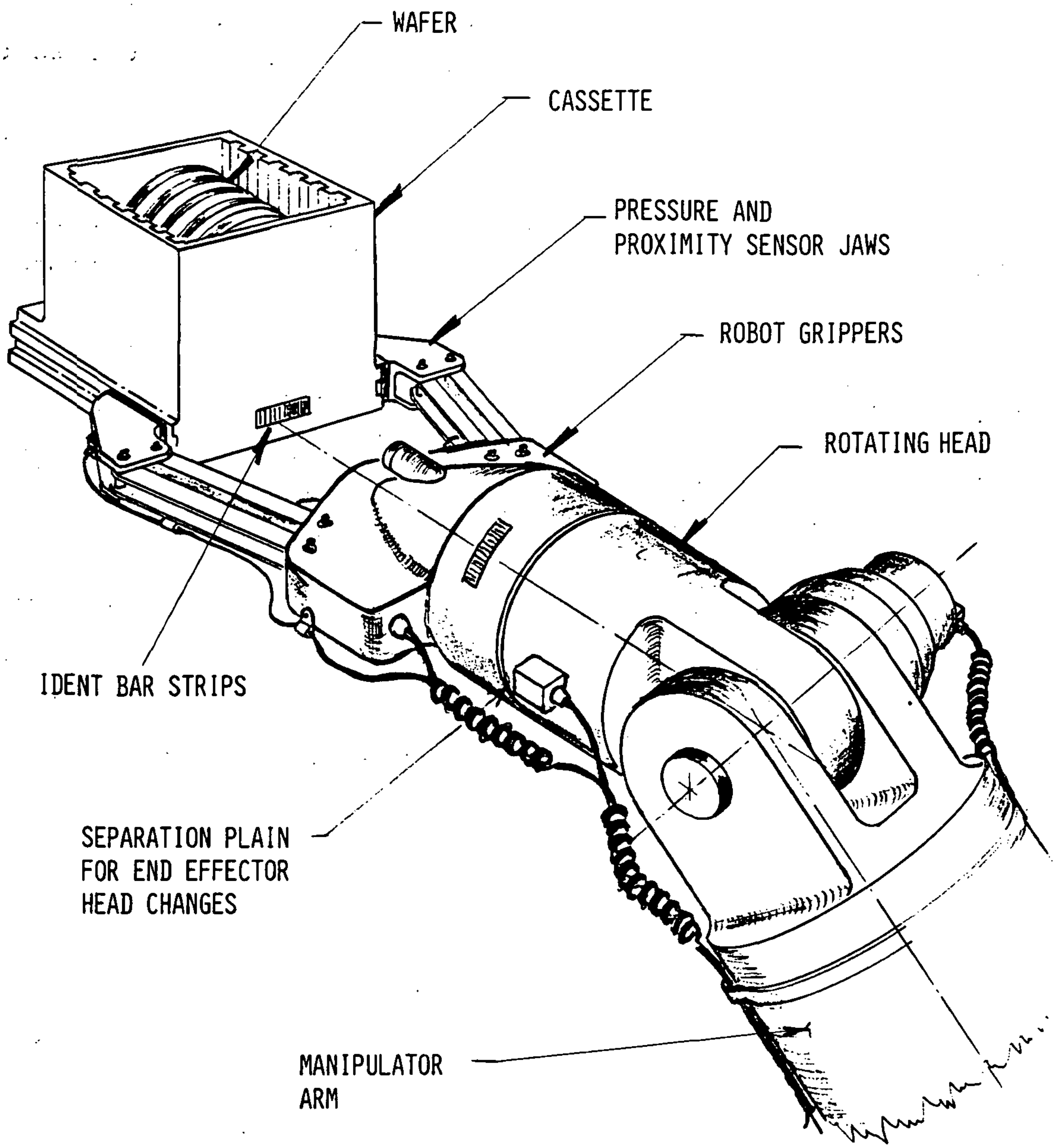
3.3.3 ARTIFICIAL INTELLIGENCE (AI)

Of course the crystal production facility requires computer control. This computer would contain software to perform the functions shown in Figure 3.3-4.

- SYSTEM EXECUTIVE
  - SYSTEM INITIALIZATION
  - PERFORMANCE REQUIREMENTS UPDATES*
  - TRENDING/STATUS REPORT GENERATION
  - EXTERNAL INTERFACE ACTIVATION
  - EVENTS SCHEDULING*
- SYSTEM FAULT DETECTION & HANDLING
  - FAULT DETECTION
  - FAULT HANDLING*
- SYSTEM MONITOR
  - MONITOR
  - CONTROL

*POTENTIAL AI APPLICATIONS

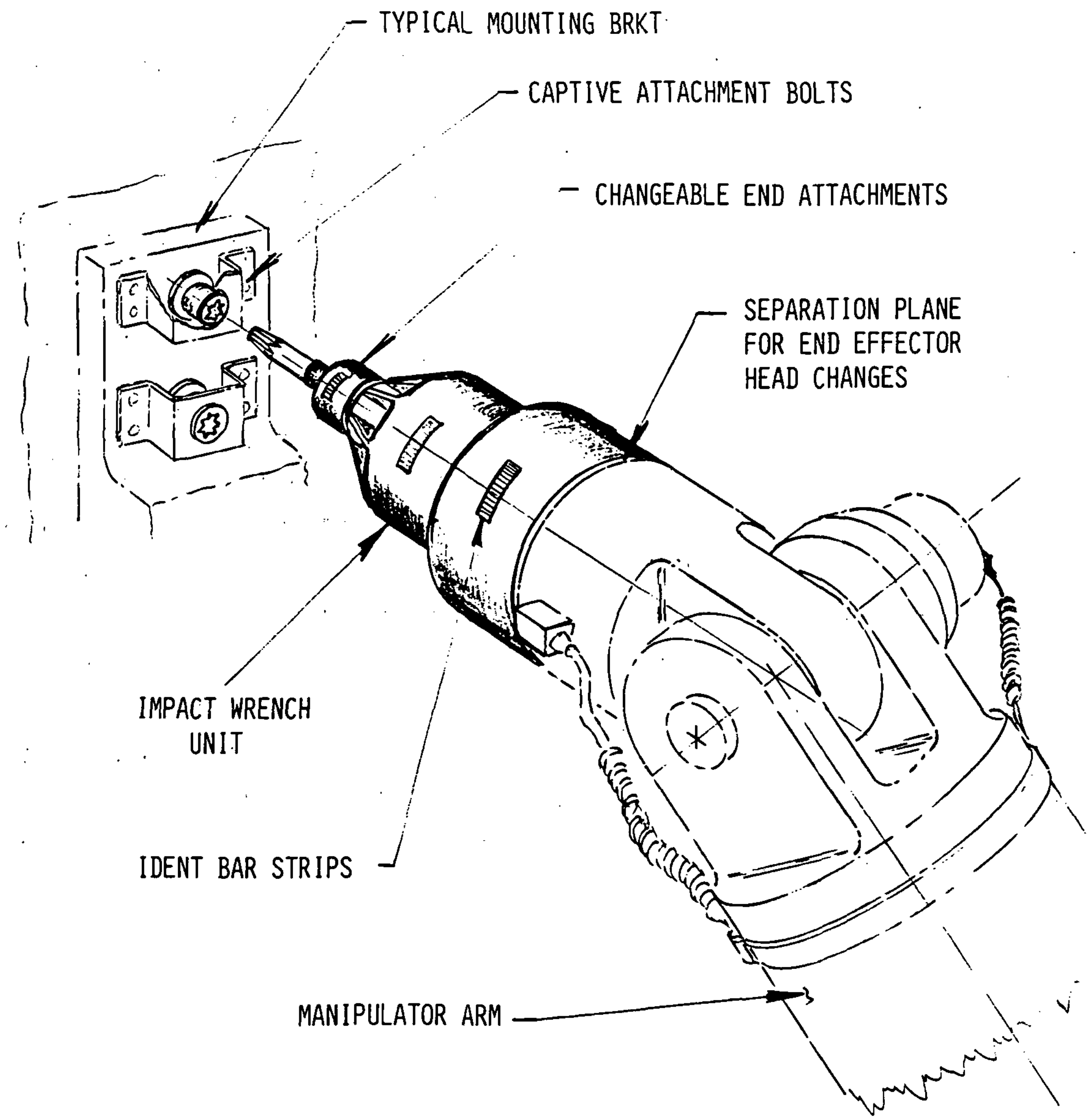
Figure 3.3-4 Executive Controller Requirements



CASSETTE GRIPPERS

MANIPULATOR AND EFFECTOR

Figure 3.3-2 Cassette Gripper End Effectors



TOOL HEAD

MANIPULATOR END EFFECTOR

Figure 3.3-3 Tool Head End Effector

Some of these functions are straight forward decision making according to defined algorithms. However some of the functions could benefit from AI.

The kinds of functions that AI systems should perform and the types of knowledge they will have to work with are fairly well understood. However much development will have to take place between now and the 1990 time frame so that the crystal growth manufacturing facility can incorporate these functions into the automatic and robotic systems of a space born application. It is felt that the Crystal Production concept and AI can grow together.

Early areas of incorporation will be in the areas of process planning, control and troubleshooting. In later areas of maintenance, repair and refurbishment, AI systems will have a very important role to play, eventually doing away with the need for any crew intervention, and creating a totally autonomous facility. However, this emphasizes the need for incorporating future AI requirements into the design process from the beginning. The design team will have to include an AI expert who can reasonably estimate such future requirements as new and different sensors and increased computer memory.

4.0 GaAs MICROELECTRONICS CHIP PROCESSING FACILITY

As further response to NASA's request for informed technical guidance in the use of automation and autonomous systems, General Electric has developed the GaAs Microelectronics Chip Processing concept as a follow-on to the GaAs Crystal Production and Wafer Manufacturing scheme. The GaAs Chip Processing Facility represents an innovative, technologically advanced, fully automated manufacturing process. The concept was developed to facilitate an in depth analysis of automation requirements including process mechanization, teleoperation, robotics and artificial intelligence. The process differs significantly from the crystal production and should uncover different automation requirements.

The conceptual design of the Chip Processing Facility is shown in Figure 4.0-1. The layout depicts each of the process subsystems and cassette transport robot arms as contained in a standard Space Station module. The module will be unpressurized when the facility is in production. The main reason for doing the VLSI fabrication in space is the ease of getting a high vacuum with ultra low contamination levels. VLSI yield is proportional to contamination level and as feature sizes are decreased it becomes even more sensitive. It may be desirable to combine a wake shield with the module to reduce the vacuum level lower and speed up the pump down.

For purposes of this study, the latest terrestrial state-of-the-art (SOA) manufacturing methodologies and equipment have been baselined into the facility design. Individual process subsystems are already fully automated and will require little technological advancement for space application besides space qualification . However, an advanced automation scheme, perhaps only being conjectured by present manufacturers, has been developed to interface the various process subsystems for both

material handling and process control. Figure 4.Ø-2 depicts the process subsystems and associated process flow lines. The flow lines represent process paths requiring robotic intervention for wafer cassette transport.

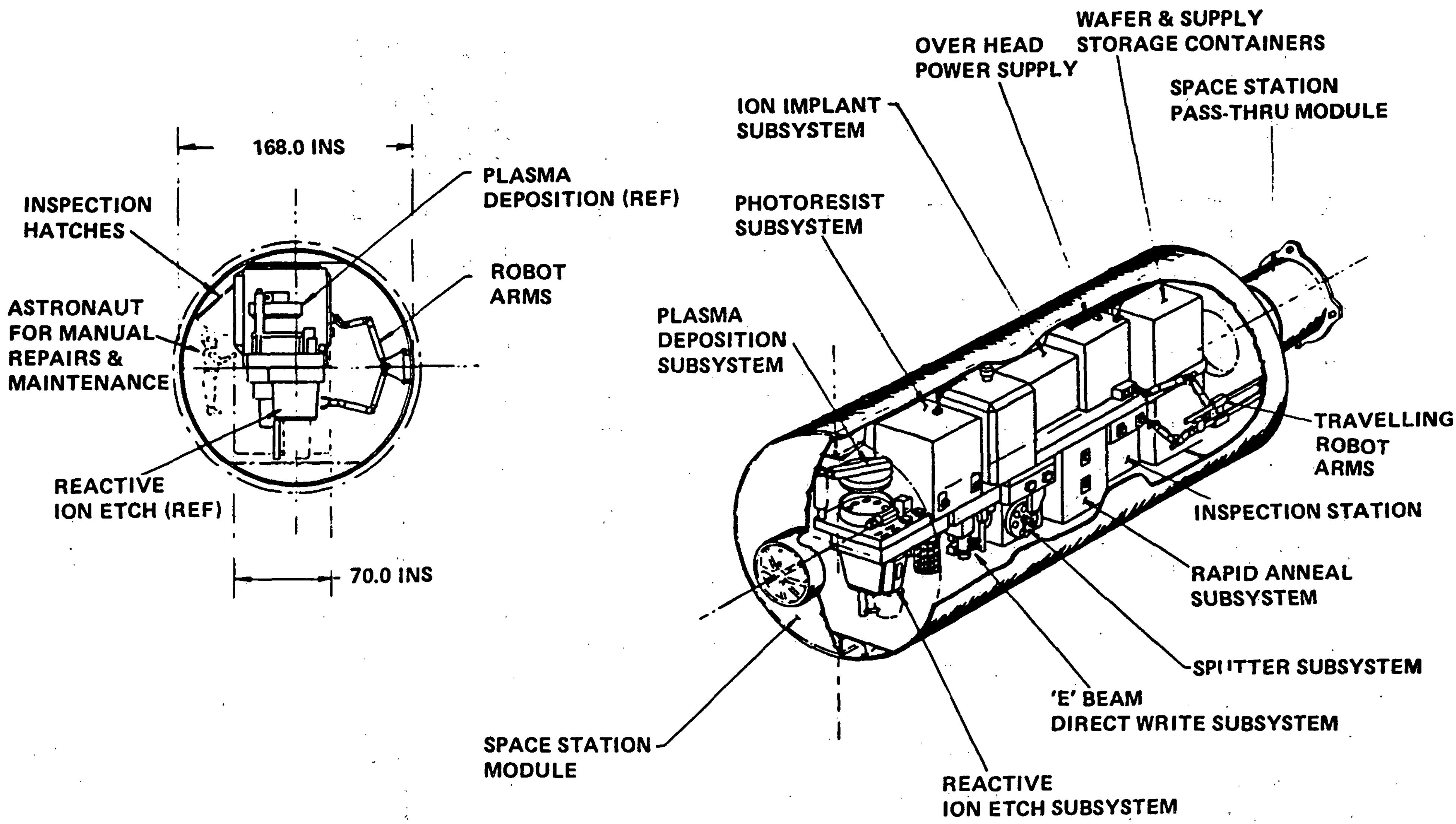


Figure 4.0-1 GaAs Microelectronics Chip Processing

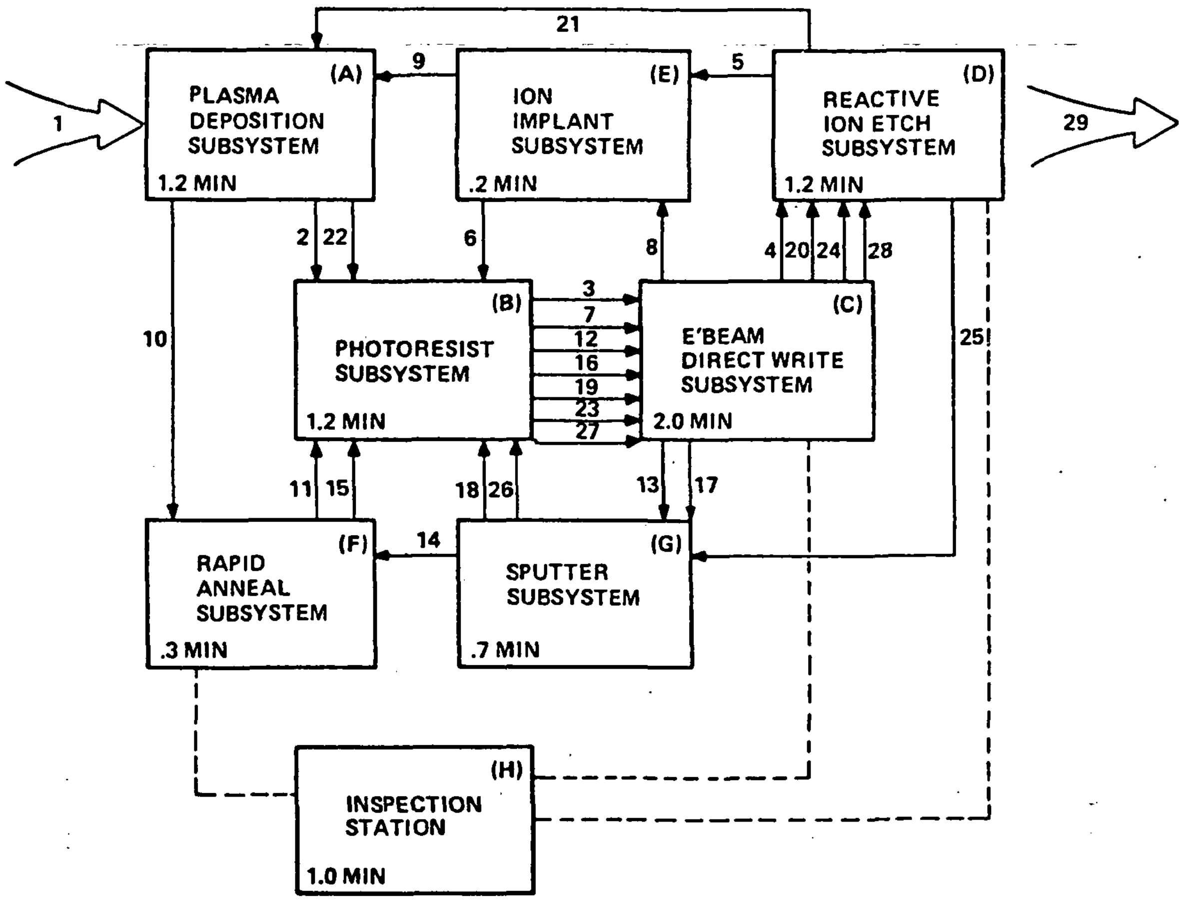


Figure 4.Ø-2 Microelectronics Chip Processing Flow

The automation scheme is presented in Section 4.3, which highlights the mechanization, robotics, and artificial intelligence associated with process control, quality assurance, and maintenance. Prior to the automation discussion, Sections 4.1 and 4.2 describe the proposed facility by defining process methodologies and associated equipment.

4.1 PROCESS DESCRIPTION

The fabrication of GaAs chips in space involves a series of complex process steps beginning with polished GaAs wafers and ending with wafers which contain hundreds of chips, each representing thousands of microelectronic elements.

Figure 4.1-1 represents the overall space fabrication process and identifies the non-contamination sensitive packaging steps to be performed in a terrestrial setting. The concept, as developed by GE's Microelectronics Center, utilizes a seven mask process to fabricate the desired device. The patterns for the seven mask levels are generated by a newly developed electron-beam direct writing technique.

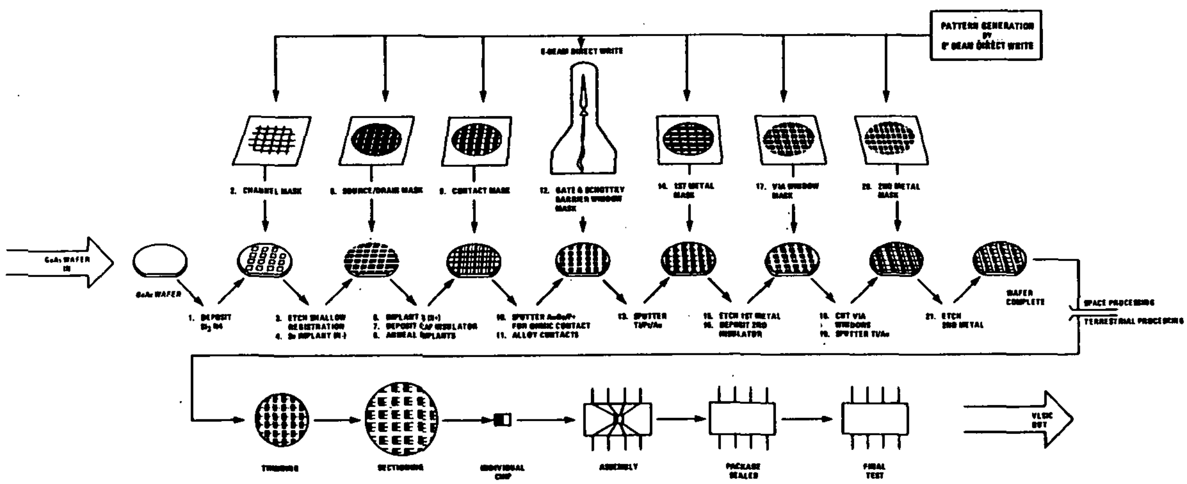


Figure 4.1-1 GaAs VLSI Fabrication Schematic 7 Mask Process

The process begins with a polished GaAs wafer, typically about one half millimeter thick and one hundred to one hundred twenty five millimeters in diameter. During fabrication the GaAs wafer is subjected to a series of complex process steps, including: film deposition, electron beam lithography, ion implantation, ion etch, sputter deposition, and annealing as shown in Figure 4.0-2. To facilitate tight quality control, elaborate monitoring and inspection subsystems need to be incorporated to minimize human intervention.

The structure of the GaAs integrated circuits is complex both in topography of its surface and in its internal composition. Each element of the chip represents an intricate three dimensional architecture requiring consistent reproduction in every circuit. As shown in the masking sequence below, the chip design incorporates seven mask layers to produce detailed electrical patterns. Each mask layer must meet rigid pattern specifications, thus requiring precise process control and effective quality control.

4.1.1 SEVEN MASK PROCESS

4.1.1.1 First Mask

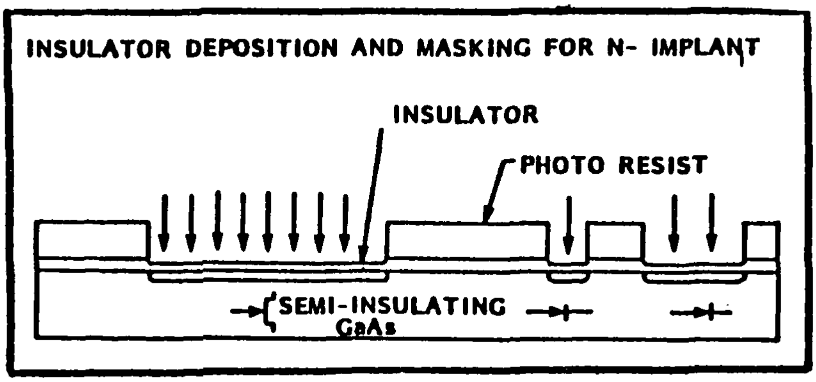


Figure 4.1-2 a

Process	Subsystem	Description
a. Deposit Si_3N_4	Plasma Depositor	Silicon nitride is deposited using a chemical vapor technique to serve as an oxidation mask.

b.	Generate Channel Mask	Photoresist Processor; E'beam Direct	PMMA (photoresist) applied; pattern for initial channel is written using vector scan direct write technique.
c.	Etch Shallow Registration	Reactive Ion Etcher	Shallow registration associated with initial channels are etched using a reactive ion etching technique.
d.	Implant Selenium (Se)	Ion Implanter	Selenium ions are implanted into insulating substrates to serve as n-type dopants.

4.1.1.2 Second Mask

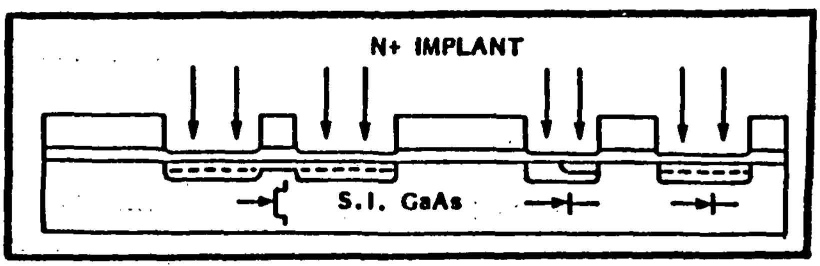


Figure 4.1-2 b

	Process	Subsystem	Description
a.	Generate Source Drain Mask	Photoresist E'Beam Direct Writer	PMMA applied; source and drain patterns written.

b. Implant Sulfur(s)	Ion Implanter	Sulfur ions implanted are implanted into insulating substrates to serve as n+ dopants.

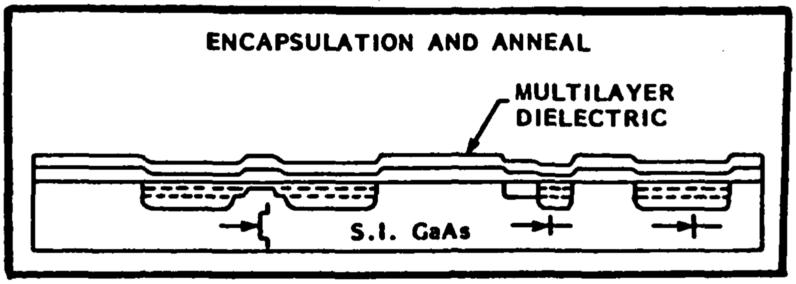


Figure 4.1-2 c

c. Deposit $Si\emptyset_2$ CAP Insulator	Plasma Depositor	Silicon dioxide is deposited to encapsulate insulting layer using a plasma enhanced chemical vapor deposition technique.
d. Anneal Implants	Rapid Annealer	Annealing "heals" ion implantation damage by administering the appropriate combination of time and temperature.

4.1.1.3 Third Mask

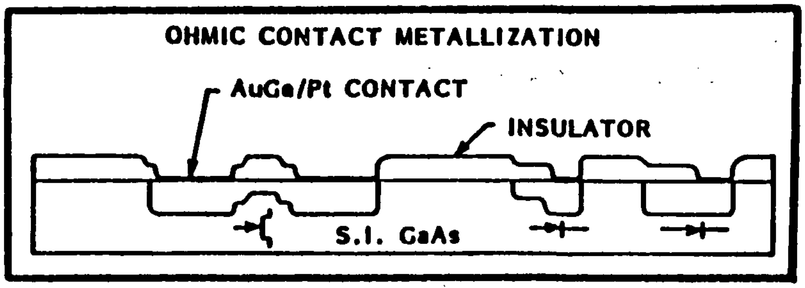


Figure 4.1-2 d

Process	Subsystem	Description
a. Generate Contact Mask	Photoresist Processor; E'Beam Direct Writer	PMMA applied; contact pattern written using direct write techniques.
b. Sputter Metal (AuGe/Pt) (Ohmic Contact)	Sputterer	Gold germanium and platinum ions are sputtered to form the low resistance baseline required for ohmic contact.
c. Alloy Contacts	Rapid Annealer	Heat treatment lowers barrier height, further enhancing the in-diffusion of germanium, and supports gettering effect of gold.

4.1.1.4 Fourth Mask

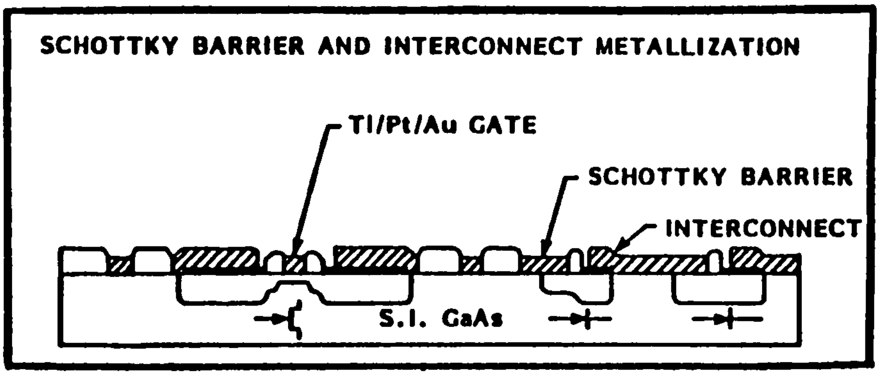


Figure 4.1-2 e

	Process	Subsystem	Description
a.	Generate Gate & Schottky Barrier Window Mask	Photoresist Processor; E'Beam Direct Writer	PMMA applied; gate and Schottky barrier E'beam Direct window patterns Writer written using direct write technique.
b.	Sputter Ti/Pt/Au	Sputterer	Titanium/platinum/ gold ions are sputtered onto wafer surface to produce desired barrier height

4.1.1.5 Fifth Mask

	Process	Subsystem	Description
a.	Generate First Metal Mask	Photoresist Processor; E'Beam Direct Writer.	PMMA applied; first metal pattern written.
b.	Etch First Metal	Reactive Ion	Desired pattern is etched into metal layer using reactive ion etch technique.
c.	Deposit Second Insulator	Plasma Depositor	Second insulator layer deposit using plasma enhanced chemical deposition technique.

4.1.1.6 Sixth Mask

	Process	Subsystem	Description
a.	Generate VIA Window Mask	Photoresist processor; E'beam Direct Write	PMMA applied; VIA window patterns written.
b.	Cut VIA Windows	Reactive Ion Etch	VIA windows are opened using reactive ion etching.
c.	Sputter Ti/Au	Sputterer	Titanium and gold ions are sputtered onto wafer surface.

4.1.1.7 Seventh Mask

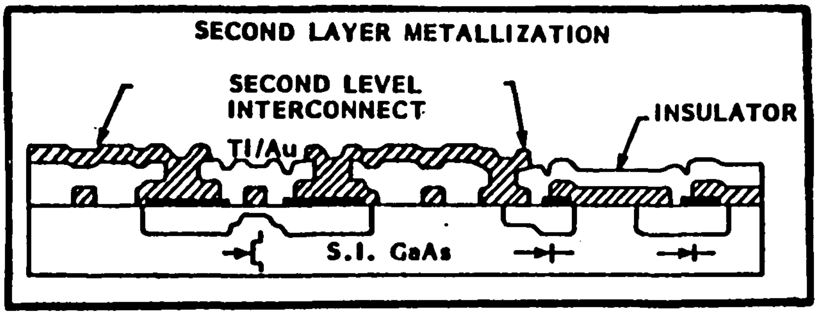


Figure 4.1-2 f

Process	Subsystem	Description
a. Generate Second Metal Mask	Photoresist processor E'Beam Writer	PMMA applied metal pattern written using direct write technique.
b. Second Metal Etch	Reactive Ion Etcher	Final metal layer etched via reactive ion etch process.

4.1.2 QUALITY CONTROL

The successful manufacture of GaAs chips in space will require a technologically advanced quality control system. Much of the detailed in-line inspection performed during terrestrial fabrication will, of necessity, be eliminated from the space fabrication process. Physical dimensions and the desire to limit human intervention, preclude the use of multiple inspection stations presently associated with each process station in earth based facilities. For this reason, an expert process

controller (EPiC) containing a substantial knowledge-base is needed to tackle the complexities of the Quality Assurance (QA) challenge. A detailed discussion of the proposed QA expert controller appears in Section 4.3.3, but suffice to say here that effective quality control will require a synergistic blend of SOA process sensors and advanced endpoint inspection techniques.

As envisioned, the quality control challenge will be met on two levels: individual subsystem monitoring and periodic wafer inspection. The electrical, mechanical, and optical sensors used to evaluate process subsystem performance exist today, and are incorporated into each of the subsystem designs selected for space application. Potential analysis involves four areas of diagnostic application as shown in Figure 4.1-3: Morphology Determination, Chemical Analysis, Crystallographic Structure and Mechanical Properties Determination, and Electrical Mapping. The extent of diagnostic analysis in each of these areas, can be determined only after actual chip design is identified.

The QA concept also includes a dedicated wafer inspection station which randomly inspects wafers at various stages of the fabrication process, as tasked by EPiC. Control chips, referred to as TEG's (Test Element Groups) as depicted in Figure 4.1-4 would undergo electrical probing to determine device quality with respect to: threshold voltages, gain constants, capacitance, breakdown voltage, resistance and leakage currents. Based upon performance trends, EPiC would then suggest/implement corrective measures as appropriate.

4.1.3 SCHEDULING

An initial process scheduling scheme was developed to avoid process "bottlenecks". Accordingly, cassette wait states during processing were to be avoided. However, this approach to scheduling did not maximize process equipment utilization and therefore was abandoned.

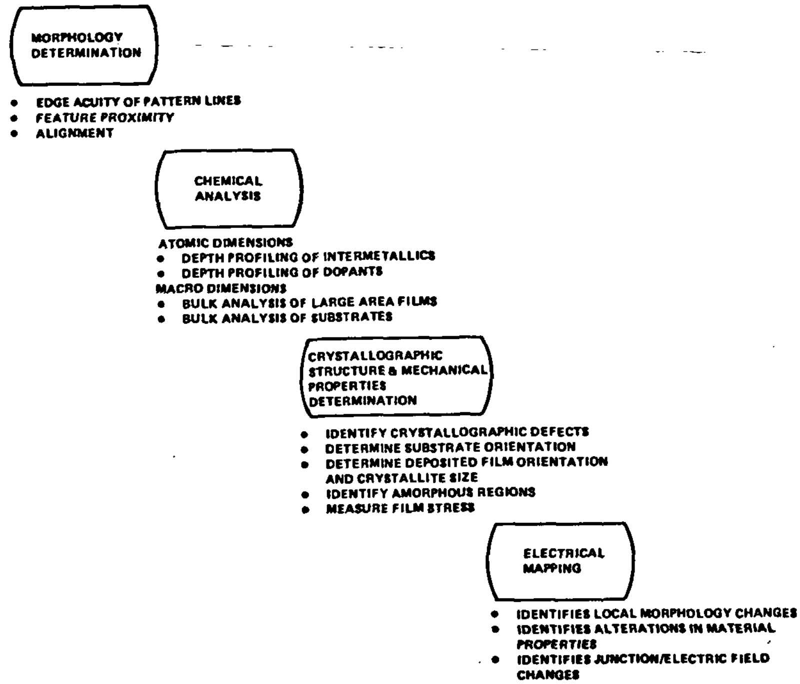
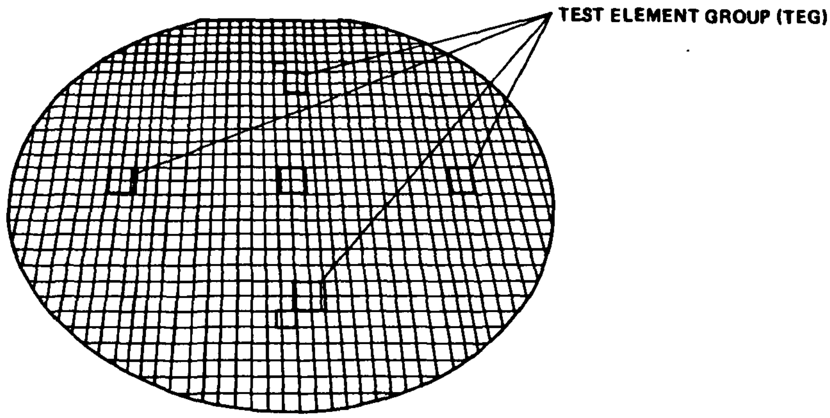


Figure 4.1-3 Potential Diagnostic Areas for Quality Control



PARAMETERS TESTED INCLUDE:
(OF POSSIBLE 73)

THRESHOLD VOLTAGE
- GATE
- FIELD

GAIN CONSTANT
- GATE

CAPACITANCE
- INTERLEVEL
- JUNCTION
- PARASITIC EDGE

BREAKDOWN VOLTAGE
- JUNCTION BREAKDOWN
- DIELECTRIC RUPTURE
- ACTIVE AREA
- INTERLEVEL

RESISTANCE
- SHEET RESISTANCE
- SOURCE DRAIN
- CONDUCTIVE LAYERS
- ACTIVE AREAS
- CONTACT DOPANTS
- SPECIFIC CONTACT RESISTANCE

PUNCHTHROUGH VOLTAGE
- HORIZONTAL
- VERTICAL

LEAKAGE CURRENT
- JUNCTION
- SOURCE/DRAIN
- DIELECTRIC

Figure 4.1-4 Electrical Parameters Tested by TEG's

A	PLASMA DEPOSITION	1.2 min.	F	RAPID ANNEAL	0.2
B	PHOTORESIST PROCESSING	.8	G	SPUTTERING	0.6
C	E'BEAM DIRECT WRITE	2.0	H	INSPECTION	1.0
D	REACTIVE ION ETCH	1.2	▌	TRANSIT TIME	0.4
E	ION IMPLANT	0.2			

Figure 4.1-5 Automated Process Timeline

Further evaluation of the scheduling challenge has suggested that a free-running "first-in-first-out" production line would facilitate maximum productivity and equipment utilization. Staging areas would be incorporated into each process station, where arriving cassettes could be retained until the station is cleared of previous cassettes. Cassettes would be processed in the order in which they arrived, first-in-first-out. Cassette bar codes would be read by sensors on both the robot arm transporter and the receiving process station to ensure proper routing and processing. Figure 4.1-5 represents the scheduling routine and timing necessary to process an individual GaAs wafer. Timing for batch processing can be derived by multiplying the process times by the number of wafers in each cassette; transit times remain unchanged.

4.2 EQUIPMENT REQUIREMENTS

The process subsystems described herein represent state-of-the-art technology in terrestrial chip fabrication equipment. The process subsystems found in earth based facilities are typically stand-alone, separate pieces of equipment, manufactured by various vendors. Current designs incorporate their own microcomputer, and demonstrate standardized software and handling mechanisms. Wafer loading is accomplished by people in "clean rooms" using standardized cassettes containing up to 25 wafers. A vacuum environment must be accomplished individually by most subsystems during the fabrication process.

In arriving at subsystem designs for space application, certain simplifications have been introduced. First, the vacuum of space allows a major simplification of those subsystems requiring vacuum for processing. The vacuum pumps and plumbing associated with these subsystems has been eliminated, thus freeing up much needed volume in the manufacturing module. Further simplification is made possible by integrating the individual subsystem controllers into a centralized, remotely located process controller. And lastly, the microgravity of space permits much of the mass volume associated with terrestrial equipment to be significantly reduced.

The subsystems selected for space conversion were identified by GE's Microelectronic's Center, as presenting the latest in fully automated chip processing technology. Numerous vendor consultations resulted in the following subsystem descriptions and associated space modifications. Process requirements for each subsystem are highlighted in Figure 4.2-1.

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PROCESS REQUIREMENTS	PLASMA DEPOSITION SUBSYSTEM	PHOTORESIST PROCESSING SUBSYSTEM	E'BEAM DIRECT WRITE SUBSYSTEM	REACTIVE ION ETCH SUBSYSTEM	ION IMPLANT SUBSYSTEM	RAPID ANNEAL SUBSYSTEM	SPUTTERING SUBSYSTEM
PROCESS TIME	1.2 MIN/WAFER	0.8 MIN/WAFER	2.0 MIN/WAFER	1.2 MIN/WAFER	0.2 MIN/WAFER	0.2 MIN/WAFER	0.8 MIN/WAFER
PROCESS MATERIALS	SILANE GAS AMMONIA NITROGEN SILICON DIOXIDE	PMMA NITROGEN	NONE	CHLORINATED/ FLUORINATED GASES	SILICON SULFUR SELENIUM NITROGEN	ARGON GAS	GOLD PLATINUM TITANIUM GOLD GERMANIUM ARGON NITROGEN
WASTE PRODUCTS	H_2 FREON/OXYGEN CLEANING CYCLE	SPUN-OFF PMMA HMDS	HEAT	RESIDUAL GASES (RECYCLABLE)	RESIDUAL IONS	NONE	RESIDUAL GASES
VACUUM PRESSURE	5×10^{-4} TORR	9.2×10^{-4} TORR (MINIMUM)	$10^{-6}-10^{-8}$ TORR	10^{-6} TORR	NONE SPECIFIED	NONE SPECIFIED	10^{-6} TORR
ENVIRONMENTAL CONDITIONS	300°C	NONE SPECIFIED	21°C ± 0.1°C MINIMUM VIBRATION	< 40% RELATIVE HUMIDITY MINIMUM VIBRATION	< 120°	800 – 1000°C	400°C 50 – 60% RELATIVE HUMIDITY
ELECTRICAL POWER	208/220V; 70A/φ OR 380/440V; 35A/φ 3φ RF 380 kHz 6 kW	115V; 50/60 Hz 15 AMPS MAX; 5 AMPS AVERAGE	208/120V 60 Hz; 10 kVA	208V; 3φ 70 AMP, 60 Hz 400 – 600 WATTS	208V; 50/60 Hz 18 kVA MAX 3φ	208V; 3φ 60 Hz; 70A/φ	480V; 22A 50/60 Hz; 3φ 1.2 – 12 kW
SCHEDULED MAINTENANCE	AUTOMATIC CLEAN CYCLE – FREON/OXYGEN HIGH POWER DIS-CHARGE	CLEAN CYCLE – REMOVABLE EXHAUST PLENUM	APERTURE CLEANING WRITE TEST PLATES 8 HOURS/MONTH	VACUUM PUMPS/SEALS MAJOR MAINTENANCE ELIMINATED IN SPACE CHAMBER CLEANING/ SHIELD REPLACEMENT 6 HOURS/MONTH	SHIELD REPLACEMENT CHAMBER CLEANING 8 HOURS/MONTH	NONE SPECIFIED	SHIELD REPLACEMENT CHAMBER CLEANING END OF TARGET LIFE CHANGE CLIPS/TARGET 5 HOURS/MONTH

Figure 4.2-1 Subsystem Process Requirements

4.2.1 PLASMA DEPOSITION SUBSYSTEM

MAKE/MODEL: ELECTROTECH/ND5200

ELEMENTS:
- Wafer Handler
- Vacuum Load Lock
- Process Chamber
- Process Controller (include temp., gas)
- RF Generator

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4.2.1.1 Terrestrial SOA

Deposited silicon nitride and silicon dioxide films are an integral part of the GaAs chip. These films provide the encapsulating material for the final passivation of devices, and the electrical insulation between metals. Film thickness must be uniform over each device. The structure and composition of the film must be controlled and reproducible, and the method of deposition safe, reproducible and easily automated. Electrotech's ND5200 PLASMAFAB shown in Figure 4.2-2 satisfies these requirements.

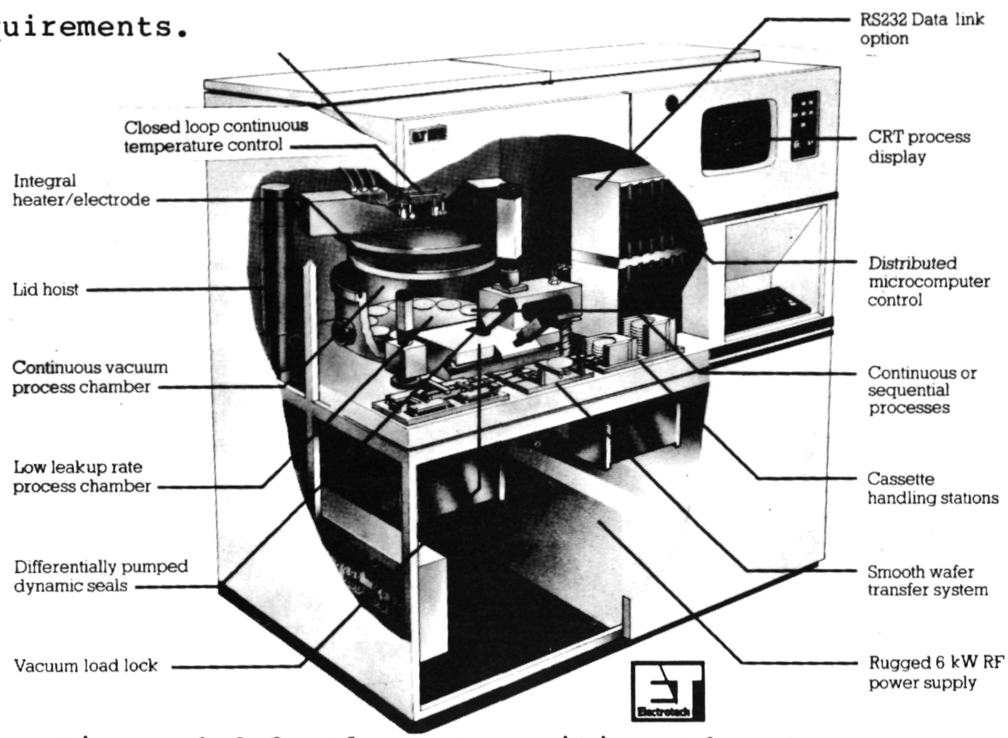

Figure 4.2-2 Plasma Deposition Subsystem

To initiate the deposition process, wafers are automatically loaded from the cassette into the process chamber, as depicted in Figure 4.2-3. To accomplish this transfer, each wafer is transported on belts to an elevating chuck where it is lowered onto the transfer arm. The arm then passes through the load lock and the wafer is transferred onto a pedestal of the rotating table in the process chamber. The handling sequence avoids front surface contact, and eliminates sliding friction, vibration, and violent accelerations thereby minimizing edge damage particulate contamination.

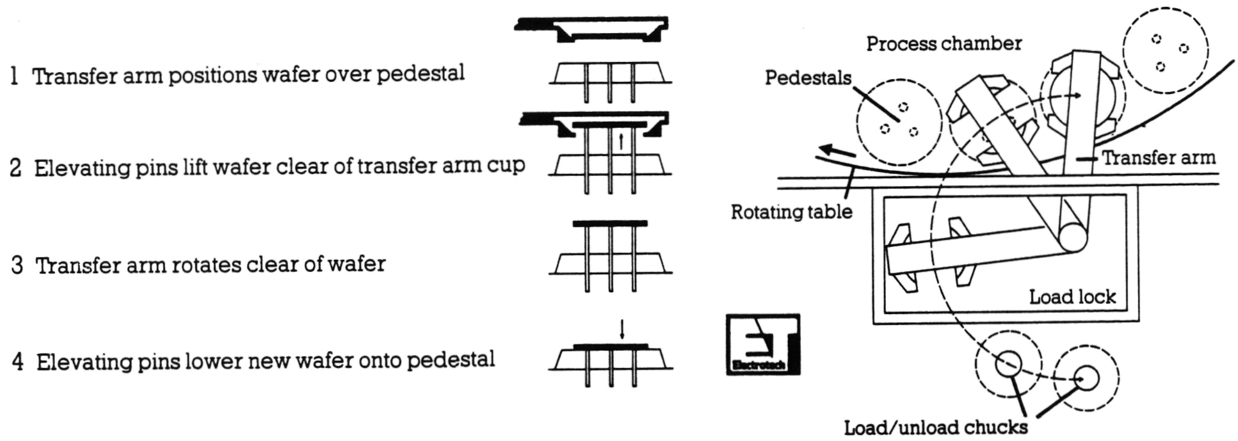

Figure 4.2-3 Wafer Handling Schematic

Once inside the process chamber, the wafer is exposed to a variety of precisely controlled process parameters including: RF, electrode spacing, power, total pressures, reactant partial pressures, temperature and process gas flow. Proper control of these variables, determines film step coverage and overall structural quality. Using a Plasma Enhanced Chemical Vapor Deposition (PECVD) process, the film is produced at low temperatures ($\approx$ 300 degrees centigrade). Plasma deposited silicon nitride is deposited by reacting silane with ammonia or nitrogen in an argon plasma. Similarly, silicon dioxide films are formed from silane and nitrous oxide in a argon glow discharge.

4.2.1.2 Space Application

Conversion of the ND5200 deposition subsystem for space use, primarily involves the simplifications cited previously. Vacuum pumps and lines are removed, along with the surrounding housing. The process controller, would be included in the centralized, remotely located process controller. The transfer arm concept for wafer handling would require slight modification to retain the wafer in the microgravity environment.

4.2.2 PHOTORESIST SUBSYSTEM

Make/Model: Eaton/LSI6000

Elements: Spindle module (spinner, scrubber, developer)
Hot/cool bake module
Process fluid dispense module
Exhaust/drain module
Microcomputer control module
Electronics modules

4.2.2.1 Terrestrial SOA

Lithography, as used in the manufacture of VLSI circuits, is the process of transferring geometric shapes on a mask or reticle to the surface of the wafer. These shapes constitute various parts of the chip, such as gate electrodes, contact windows, metal interconnections, and so on. In the first step of the lithographic process, a photosensitive polymer film is applied to the wafer, baked, and then exposed to the desired geometrical patterns by the electron beam writer. The photoresist used in conjunction with the E'beam direct writer is a positive electron resist called PMMA. A typical developer is a 1:1 mixture of methlyisobutyl ketone (MIK B) and isopropyl alcohol.

The photoresist subsystem must maintain tight tolerances in order to ensure uniform application of the PMMA. The Eaton LSI6ØØØ series, as shown in Figure 4.2-4, meets the tight control and automation requirements for space application. Using microcomputer control, the subsystem offers precision dispense systems and spin-motor controls, and repeatable bake temperatures, which result in a typical $\pm$ Ø.1 micron critical dimension across every wafer.

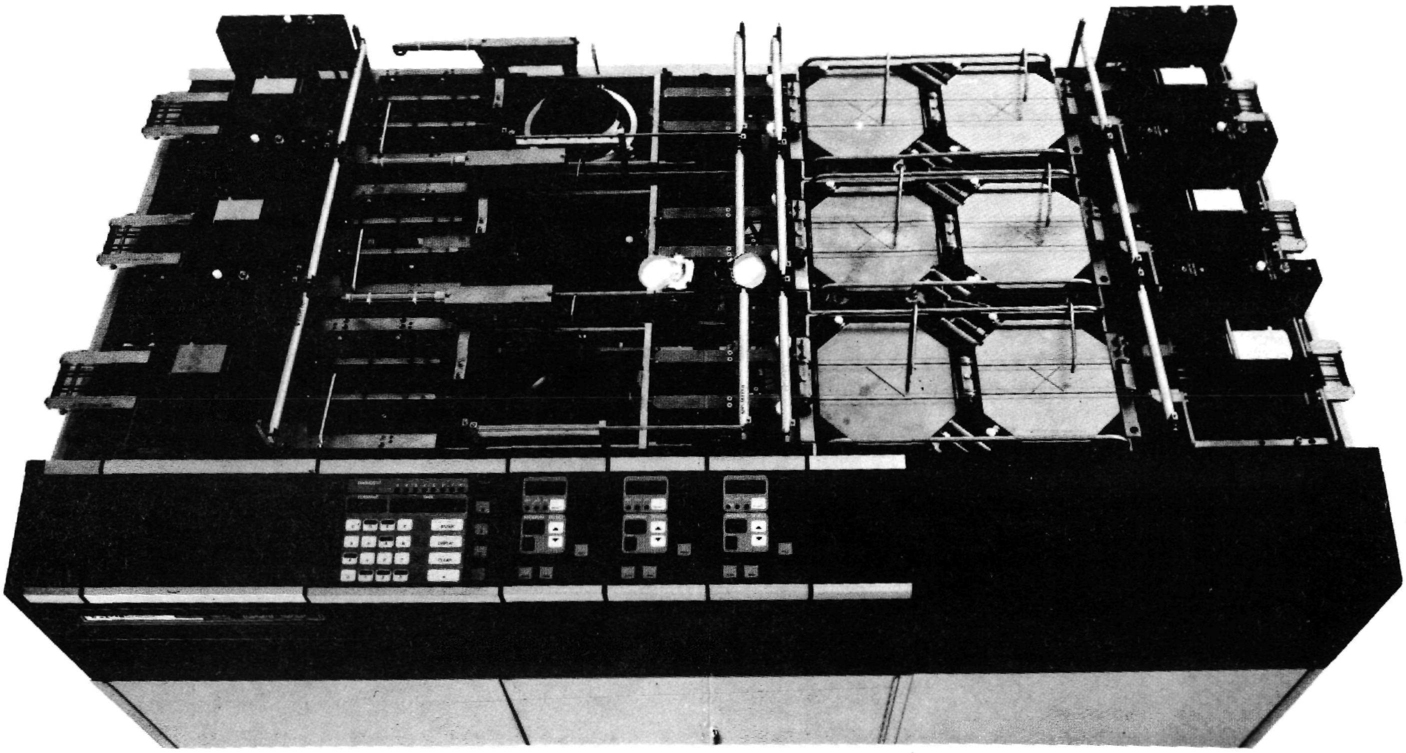

Figure 4.2-4 Photoresist Subsystem

The spindle module handles wafers cassette-to-cassette automatically. It performs photoresist coat, wafer scrub, and either positive or negative development on wafers up to five inches in diameter. As a spinner it consistently produces uniform coatings and offers a complete range of disperse capabilities. As a scrubber it utilizes a sophisticated nozzle assembly which provides high pressure and brush scrubbing. As a developer, the module offers either a negative or positive developer system with fluid temperature control to within 1 degree centigrade.

The bake module complements the spindle module by performing dehydration, soft or hard bake. As in the spindle module, wafer handling and process control are performed automatically. The hot/cool plate methodology offers highly reliable hot-plate baking in combination with controlled cooling. Controlled cooling eliminates the uncertainties inherent in cooling under ambient conditions, thereby assuring critical dimensions are satisfied and improved yield is realized.

4.2.2.2 Space Application

The photoresist subsystem offers the challenge of liquid management in space. Present methods of PMMA application need further refinement for space. The subsystem's modular design offers configuration flexibility and accessibility. Dispense systems, electronics modules and even exhaust systems, can be easily removed for maintenance and servicing by robot end effectors.

The process controller is already compatible with SECS-II, the industry Semiconductor Equipment Communication Standard, which allows the subsystem to interface with other process subsystems through simple tie lines, into the centralized process controller. The existing controller also contains diagnostic routines which can be readily incorporated into the EPiC scheme.

4.2.3 ELECTRON BEAM DIRECT WRITE SUBSYSTEM

Make/Model: Perkin-Elmer/AEBLE 150

Elements:
- Wafer Handler
- Electron Optics (Gun, Column)
- Write Chamber
- Stage
- E'Beam Control Unit

4.2.3.1 Terrestrial SOA

Initial design of the GaAs chip processing facility included a Direct-Write Wafer Subsystem to perform six of the seven lithographic processes. However, subsequent study and vendor consultations determined several advantages in using an Electron-Beam Direct Write Subsystem for all seven lithographic steps. Advantages include: smaller resist geometries (down to Ø.5 μm); wafers patterned via computer without a cumbersome mask; elimination of a process subsystem freeing up much needed space; and the technique can be highly automated. The low throughput rate (5 wafers/hour) originally associated with E'beam lithography precluded it from being considered as a multiprocess subsystem. However, Perkin-Elmer's recently announced AEBLE 15Ø automated electron beam lithography equipment dramatically reduces write times to less than two minutes per wafer thus making E'beam lithography a practical substitution for the Direct Wafer Stepper. The system depicted in Figure 4.2-5 offers a fully automated wafer handling system and highly automated operating software including machine performance analysis and calibration programs. Major contributions to the high throughput rate are the job preparation system featuring a 32-bit minicomputer, and "write-on-the fly" scheme featuring a vector-scan, variable shaped electron beam.

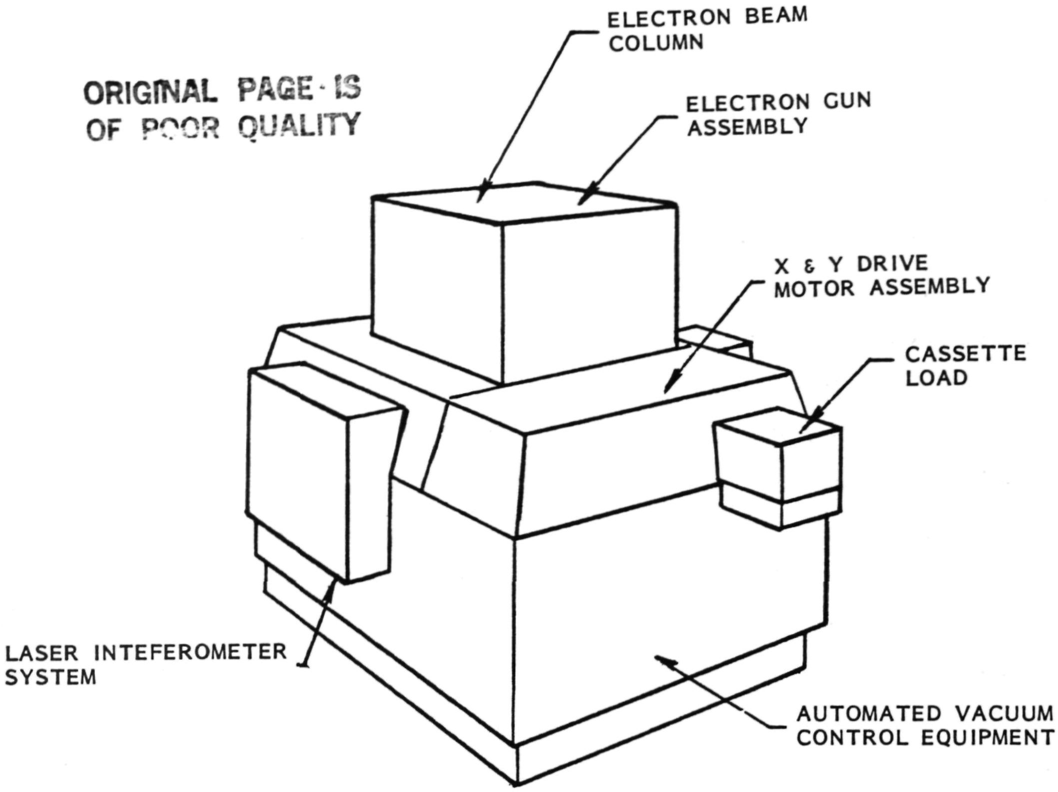

Figure 4.2-5 E'Beam Direct Write Subsystem

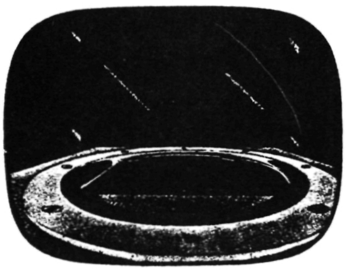

Figure 4.2-6 a

Wafers are automatically loaded into the write chamber via the wafer handling system.

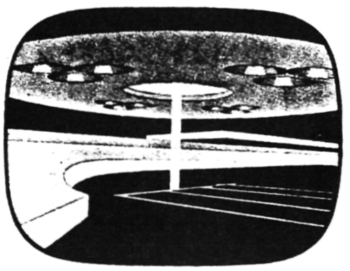

Figure 4.2-6 b

The Electron beam locates the wafer registration marks to ensure proper alignment.

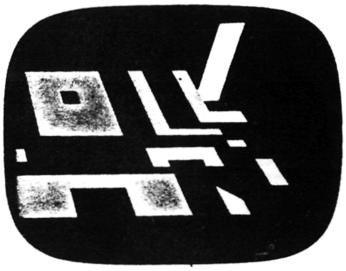

Figure 4.2-6 c

Direct writing of the desired pattern onto the wafer surface is performed using a variable-shaped electron beam in a vector scanning mode. A shaped aperture is illuminated by the electron beam and imaged onto a second aperture. By deflecting the image of the first with respect to the second, a variable shaped beam is formed and vectored to the appropriate circuit locations.

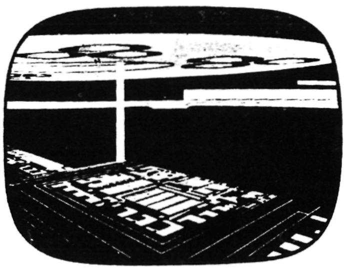

Figure 4.2-6 d

The E'beam system is extremely flexible and upgradable. Customized VLSI designs can be fabricated without going through a mask making process, by simple software alterations.

4.2.3.2 Space Application

Simplification of the E'beam direct write subsystem for space, once again involves the reduction of overall dimensions, elimination of vacuum systems, and centralizing the process control system. Because of the precision required during the write phase, tight vibration and thermal control requirements must be accommodated by the module design. Perturbations such as shuttle docking which induce vibration will have to be considered by the process scheduler. A major advantage of the subsystem for space application is its programmability which accommodates dynamic write patterns. The subsystems detailed self correct features would enhance the EPiC concept.

4.2.4 REACTIVE ION ETCH SUBSYSTEM

Make/Model: Applied Materials/AME 8100 Series

Elements:
- Autoloader
- Process Chamber (Bell jar, hexode)
- RF Matching Network
- Process Gas Flow Module
- Temperature Controller
- Process Sensors
- Process Controller

4.2.4.1 Terrestrial SOA

The etching process used for pattern transfer to the GaAs wafer must be highly selective. Ideally, neither the PMMA pattern nor previously processed features of the circuit should be removed during etching. The selectivity requirements are best met by plasma assisted dry etching techniques that use gases containing reactive constituents.

Precise etching of circuit dimensions is achieved when chemical reactions between neutral species in the plasma, and the surface being etched are influenced by directional energetic particle bombardment. The energetic particles are positive ions drawn from the plasma by an imposed electrical field. Etch rate, selectivity, and anisotropy are determined by various process parameters including, gas composition and pressure, wafer temperature, and the operating frequency and power density of the plasma. The Applied Materials AME 8100 Series Plasma Etch System, as shown in Figure 4.2-6, represents the leading edge of SOA dry etch technology.

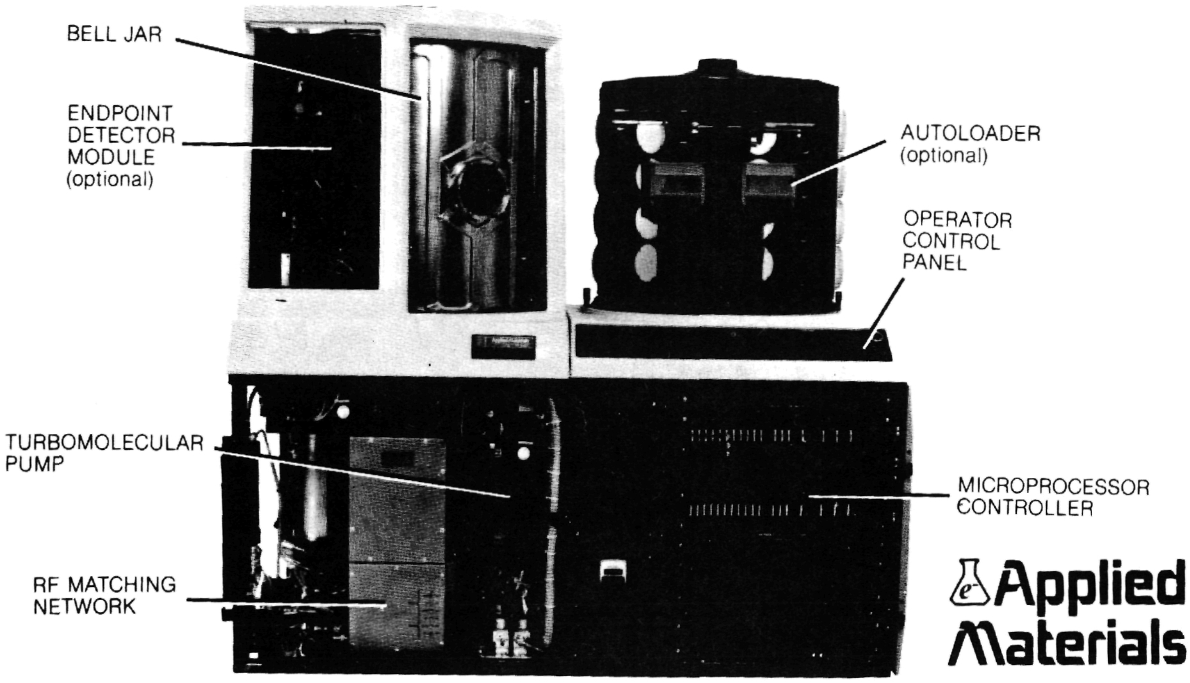

Figure 4.2-6 Reactive Ion Etch Subsystem

The AME 8100 etching process begins with the automatic loading of wafers from the cassette onto wafer trays. These trays are then loaded onto the hexode, and the bell jar lowered. The process chamber is then evacuated to approximately 10^{-6} torr.

After evacuation, the gas flow controller admits the process gas into the chamber. Gas flows through the chamber and into a feeder tube leading to a manifold inside the top of the bell jar. The gas then travels down through gas dispersion tubes placed at equal intervals around the inside of the bell jar. Flow rate and pressure are controlled by the throttle valve and the flow controllers. Pressures and flow rates are tailored to the specific etching process.

Once gas flow and pressure are stabilized in the chamber, RF power is applied to the hexode. The process controller adjusts RF power by monitoring the DC bias voltage on the hexode, or by controlling the power level to a programmed constant. The gas plasma created by the RF discharge etches the wafers until a desired endpoint is detected.

The layer endpoint sensor monitors the etching process by directing a laser beam onto the wafer surface and measuring interference signals in the reflected beam. A gas emission endpoint sensor provides a signal to the system controller when a certain gas spectrum is detected in the chamber. Chamber pressure and hexode DC potential are monitored by the sensors in the vacuum and RF systems. The hexode DC potential changes when the endpoint of the process is reached.

Once the endpoint is detected the etch process is terminated. The process gas is then evacuated from the chamber, and the chamber is backfilled with nitrogen to atmospheric pressure. At this point the bell jar is raised, the chamber opened, and the wafer trays removed.

4.2.4.2 Space Application

Current design of this subsystem requires human intervention to load the wafer trays into the hexode. However, the vendor has indicated that a fully automatic version is due out in 1985. Other modifications include vacuum pump elimination, and microprocessor removal to remote centralized process controller. Although a bell jar system must be retained it need only be designed for an order of magnitude pressure differential less than the terrestrial counterpart. As in the case of the direct write subsystem, this subsystem requires minimum vibration in order to perform the etch process, and will have to be considered in module design and process scheduling.

4.2.5 ION IMPLANT SUBSYSTEM

Make/Model: VARIAN/DF-3000

Elements:
- Wafer Handler
- Gas/Ion Chamber
- Analyzer Magnet
- High Voltage Terminal
- Lens/Aperture Modules
- Acceleration Tubes
- Scan Plates
- Target Chamber

4.2.5.1 Terrestrial SOA

The function of the ion implant subsystem is to produce an energetic beam of ions of a particular atomic species, and to direct this beam so that the ions are evenly implanted across the surface of the target wafer. VARIANS DF-3000, depicted in Figure 4.2-7, represents a high throughput multipurpose ion implanter which utilizes a filament type ion source to provide extremely stable operation over a diverse range of beam currents.

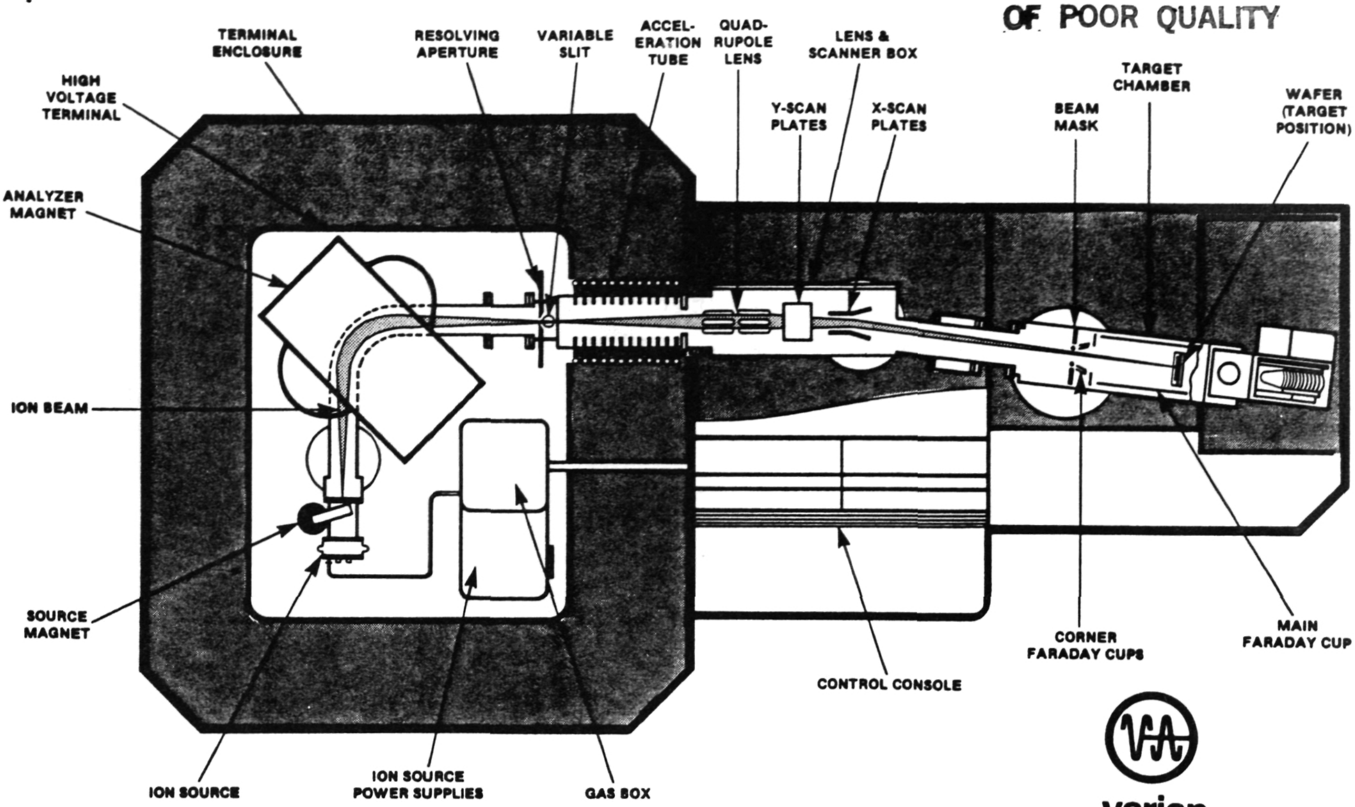

Figure 4.2-7 Ion Implant Subsystem

A hot cathode arc discharge ion source generates the ions for implant. The arc discharge is maintained by a source or carrier gas fed into a cylindrical chamber. The electron collisions with the carrier gas molecules, cause the gas molecules to separate into several species of positively charged ions. The ions are then extracted from the chamber by the electrical attraction between the source exit aperture and the extraction electrode. A voltage difference of 25 KeV between the source and the electrode causes the ions to be drawn through a slit in the chamber wall. The ions gain energy as they accelerate through the voltage differential, and leave the source as an ion beam.

Because the beam is composed of several ion species, it is necessary to separate and select those ions desired for implant. The analyzer magnet performs this function. As the ion beam leaves the source it enters the region of the transverse magnetic field, where the ions are deflected into circular orbits.

The degree of deflection is determined by the atomic mass of the particular ion. Lighter ions are deflected into tighter orbits than heavier ions. By varying the magnetic field strength of the analyzer magnet, it is possible to select only those ions desired for implant. Selected ions are deflected 90 degrees through the curvature of the magnet chamber, where the ions are focused at the resolving aperture. Undesired ions are deflected at angles less than or greater than 90 degrees and are collected on the magnet chamber walls or on the resolving aperture plate. The magnet and resolving aperture provide the separation and resolution characteristics of the implanter. The ion beam then passes through a variable slit, which by opening and closing, controls the intensity of the beam and acts as a coarse adjustment.

As the ion passes through the variable slit, it enters the acceleration tube, where the ions are given their final energy boost prior to implantation. Ions accelerate as they are drawn toward the exit. Because the beam tends to diverge as it is accelerated, a quadruple lens is positioned immediately following the acceleration tube to focus the beam into an oval shaped spot.

Now convergent, the beam is scanned by two sets of electrostatic deflection plates to ensure uniform ion distribution across the wafer. After passing through the deflection plates, the ion beam reaches the target chamber. It is in the target chamber that the ions are implanted into the target wafer. The residual electrical current produced by ions striking the wafer, is measured and used to determine the ion dose on the wafer. Once the selected dose has been implanted, the beam is removed from the implant chamber. The beam is gated electronically by a signal to the Y-plane plates which deflects the beam, preventing it from entering the target chamber. The implanted wafer is then automatically cycled out of the chamber and another cycled in.

4.2.5.2 Space Application

Modification of the ion implant subsystem will require minimum alteration for space use. The primary design change will involve the incorporation of easily accessible chamber shields to be removed and replaced. These shields will absorb the ion build-up and be removed for cleaning by robot during maintenance cycles. The dimensions associated with current thermal shielding can be significantly reduced in the space environment.

4.2.6 SPUTTERING SUBSYSTEM

Elements: Wafer Handler
Vacuum Load Lock
Preheat Station
Sputter Stations
Process Controller

4.2.6.1 Terrestrial SOA

Sputtering is a physical phenomenon involving the elevation of ions, usually Argon +, through a potential gradient, and the subsequent bombardment by the ions of a target (cathode). Through momentum transfer, atoms near the surface of the target metal (Au, Ti, Pt, AuGe) become volatile and are transported as a vapor to the substrates, where the atoms are deposited. In accomplishing this deposition process, VARIANS 3190, shown in Figure 4.2-8 represents SOA in fully automated cassette-to-cassette sputtering systems.

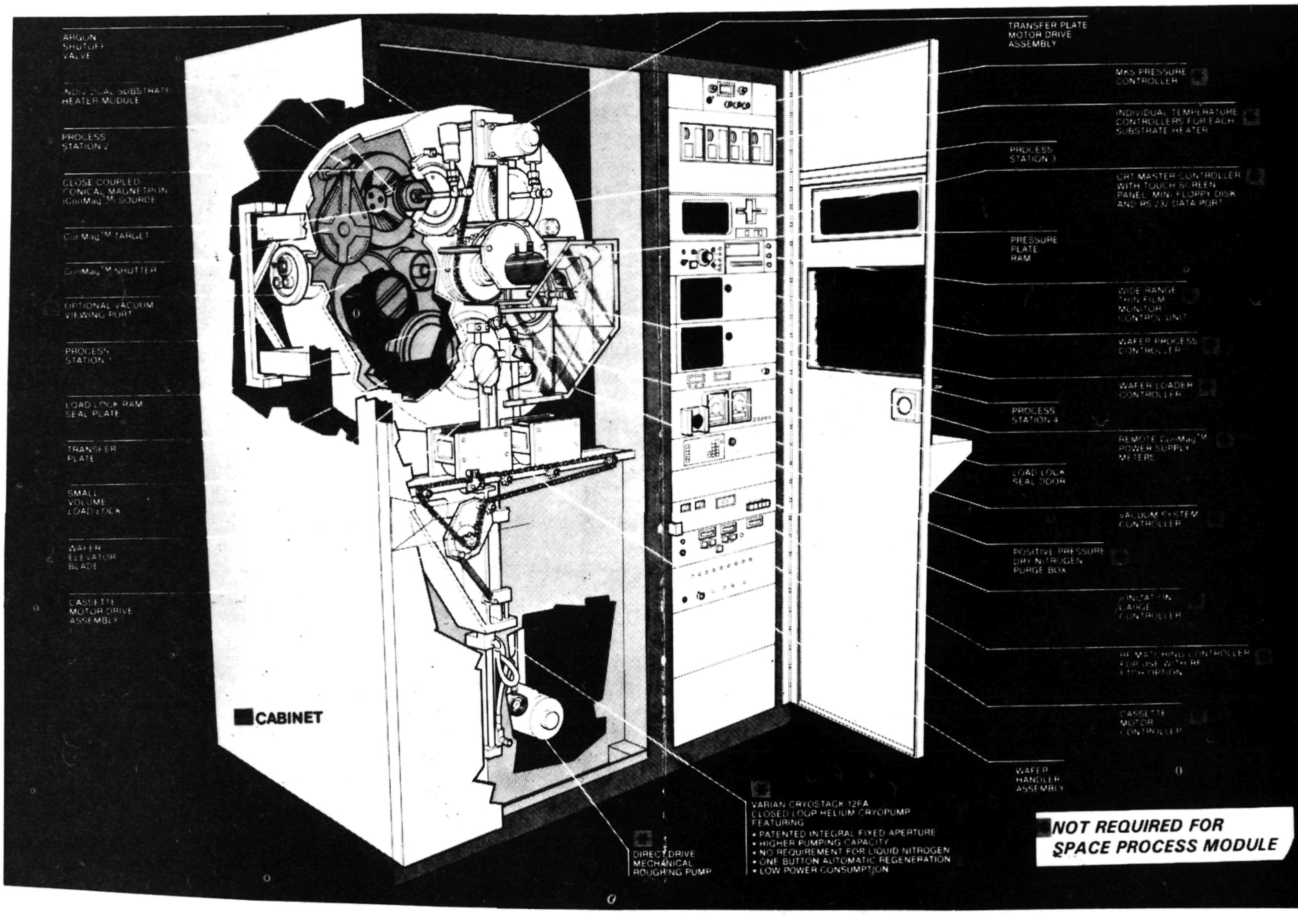

Figure 4.2-8 Sputtering Subsystem

The Varian design includes a fully automated, rotary-in-line, cassette-to-cassette, sputter-coat system featuring five active stations: one for preheat or RF etch; three for deposition plus heat; and the fifth for loading and unloading wafers.

To initiate automatic processing, a cassette of wafers is loaded onto the cassette track and engages the drive pin to properly position the cassette. The wafer flat alignment mechanism aligns all major wafer flats in the cassette at one time. The cassette is then indexed by the process controller until the first wafer is positioned above the wafer as the blade is elevated. The blade's V-groove engages the wafer as the blade is elevated. Upon activation the blade rises through the

cassette, lifting the wafer vertically to a position in front of the load door, as depicted in Figure 4.2-9. The backside vacuum pickup is then activated to hold the wafer to the door, and the blade retracts.

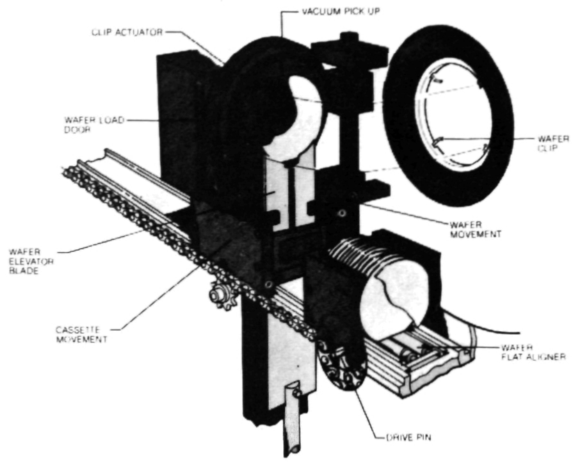

Figure 4.2-9 Wafer Handling Mechanism

The load door closes loading the wafer into the load lock and then returns to the open position as the seal door closes to seal the load lock. After the load lock pump down is complete, each wafer is indexed to each of the four process stations within the deposition chamber. The process stations perform the sputtering process as described earlier. Upon leaving the fourth process station the wafer is indexed to the load dock and returned to the original slot in the original cassette.

4.2.6.2 Space Application

The sputtering subsystem will require modifications in its wafer handling system to accommodate the vacuum and microgravity environment. Elimination of the existing vacuum pump down system will allow further reduction in physical dimensions of the subsystem.

4.2.7 RAPID THERMAL ANNEALING SUBSYSTEM

Make/Model: VARIAN/IA-200

Elements: Wafer Handler
Heater
Shutter
Anneal Station
Process Controller

4.2.7.1 Terrestrial SOA

The rapid isothermal annealing (RIA) subsystem activates dopants by heating the GaAs wafer uniformly with thermal radiation to proper annealing temperatures (800-1000 degrees centigrade). VARIAN's IA-200, shown in Figure 4.2-10, offers fully automated wafer annealing with high throughput, and minimal dopant redistribution. The subsystem incorporates radiant thermal energy to uniformly heat the wafer within ten seconds, thereby limiting dopant diffusion and retaining the implanted dopant profile.

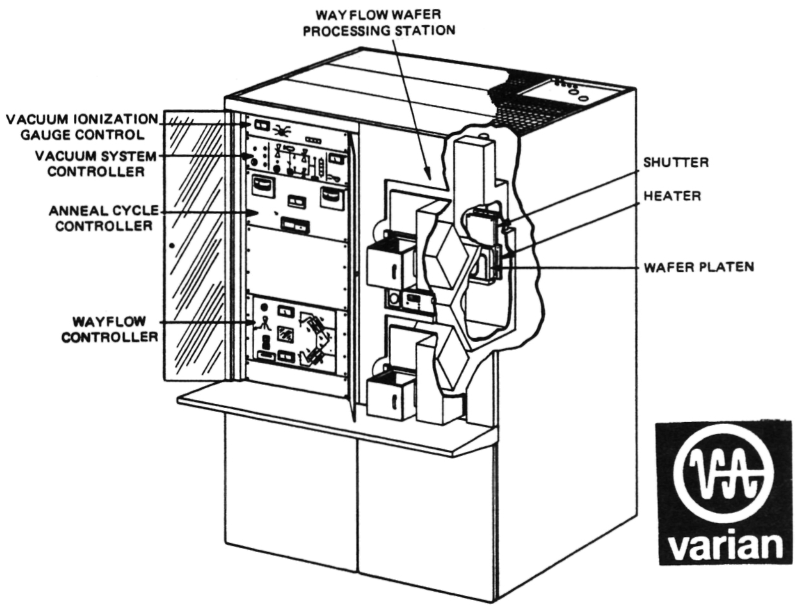

Figure 4.2-10 Rapid Isothermal Annealing Subsystem

A cassette of wafers is loaded into the subsystem's load station. The first wafer is then automatically fed into the upper vacuum lock, and onto a platen in the main vacuum chamber. An isolating shutter is opened and the wafer platen is positioned in close proximity to the graphite heater. Radiant thermal energy passes from the heat and quickly raises the wafer to annealing temperature.

Once the anneal period is complete, the wafer platen is removed from the annealing position, the isolating shutter closes, and the wafer is transferred to an exit lock after a short cool down period. Meanwhile, the next wafer is ready for loading onto the platen from the entrance lock, and the process is repeated.

4.2.7.2 Space Application

Conversion of the RIA Subsystem will require minimal design change for space application. The subsystem performs a straight forward heat treatment process requiring no special consideration for space, other than residual heat management. Use of direct concentrated solar energy was considered feasible but not practical because of scheduling limitations.

4.3 AUTOMATION CONCEPT ASSESSMENT

To provide the desired technical guidance in the use of autonomous manufacturing systems, the GaAs Microelectronics Chip Processing automation concept has been developed. The automation concept encompasses a continuous spectrum of increasingly autonomous equipment ranging from straight forward process mechanization, to teleoperation and adaptive robots, to expert controllers for process and maintenance control.

As envisioned, the automation scheme incorporates an evolutionary approach to the unique challenges of space manufacturing. The primary challenges, as identified by this study, include the automation of maintenance, repair, and servicing functions. Initially, these functions will be handled on a teleoperation basis until a sufficient knowledge-base is established. As maintenance and refurbishment anomalies are encountered, analyzed, and handled, progress in the enabling technologies will evolve into adaptive maintenance robots and ultimately into "intelligent" robots using expert control.

Conversely, automation of the fabrication process presents less design challenge, as the associated process mechanization and material handling schemes represent state-of-the-art technology. Development of an expert process controller represents a major challenge, and will also be under taken as a evolutionary process. The automation requirements for the GaAs Microelectronic Chip Processing Facility are summarized in Figure 4.3-1.

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4.3.1 PROCESS MECHANIZATION

The process mechanization requirements as defined in Figure 4.3-1 represent terrestrial state-of-the-art technology. Each of the process subsystems described in Section 4.2 offers fully automated process capabilities, and only requires design changes for application in the microgravity and high vacuum of space.

	AUTOMATION FUNCTIONS	SPACE AUTOMATION TECHNOLOGY ASSESSMENT
ROBOTICS	**PROCESS TRANSPORTERS** • Remove Wafer Cassette from Process Station Unload Area • Transport Cassette to Next Process Station as Determined by Cassette Bar Code • Place Cassettee Into Load Area of Next Process Station **INSPECTION TRANSPORTER** • Remove Random Cassette From Process Station Unload Area, as Directed by EPC • Transport Cassette to Load Area of Inspection Station • Remove Inspected Cassette from Inspection Station Unload Area and Transport to Appropriate Process Station	Robotic transport applications are straight forward, however technology for handling the light and fragile cassettes in the space station environment need further development. (No terrestrial counterpart). Robot arms must be sensitive to proximity of other arms and process station locations to ensure smooth cassette transportation without collision. Vision systems for robotic debris retrieval must be developed.
	MAINTENANCE TELEOPERATOR/ROBOT • Remove/Replace Bad Electronic Cards • Remove/Replace Filters, Shields • Remove/Replace Horn Filaments • Remove/Replace Lenses • Refurbish Materials (i.e., Sputter Targets Au, Pe, Ti) • Conduct Process Equipment Checks • Perform Unscheduled Cleaning Tasks When Necessary	Maintenance robot applications will require significant development. currently, all maintenance functions are performed manually on terrestrial process equipment. Robot must be capable of handling moderately complex repair, cleaning, and refurbishment tasks in the microgravity environment. Advanced vision and tactile sensors will be required. Robotic maintenance applications will evolve from initial teleoperation to an ultimate "intelligent" robot.
ARTIFICIAL INTELLIGENCE	**EXPERT PROCESS CONTROLLER (EPIC)** • Assimilate Process Monitoring Inputs (Process Sensors, Inspection Station) • Identify Wafers for Inspection • Interpret Process Deficiencies • Identify Effects of Corrective Actions (Based on Actual Models) • Review Effects of Suggested Process Adjustments • Determine Best Course of Action • Implement Required Process Adjustments, Tracks Results • Reconfigure Automation Timeline to Accommodate Process Adjustments • Reforecast Raw Materials Wage and Waste Materials Timeline	EPIC will require full development, as there is no applicable terrestrial system in existence. The complexities of chip processing, coupled with the logistic challenges of space demand the timely trouble-shooting and process control knowledge base that an expert system offers.
	EXPERT MAINTENANCE CONTROLLER • Perform Process Equipment Checks as *Dictated by Equipment Performance* • Flag Abnormal Transient Operation Prior to Hard Failure of Process Element • Isolate Equipment Faults, Troubleshoot, Interpret Best Couse of Action from Knowledge Base.	As in the case of EPIC, the expert *maintenance* controller will require full development. The knowledge base will have to account for equipment parameters and idiosyncrasies as well as the effects of the space environment on equipment performance.
PROCESS MECHANIZATION	**PLASMA DEPOSITION SUBSYSTEM** • Load/Unload • Deposit Film (Plasma Enhanced Chemical Vapor Deposition) **PHOTORESIST PROCESSING SUBSYSTEM** • Load/Unload • Perform Water Scrub • Apply photoresist Coat • Develop Positive/Negative Resist • Perform Bake, Dehydration **ELECTRON BEAM DIRECT WRITE SUBSYSTEM** • Load/Unload • Register Wafer • Perform Ebeam Direct Write (Vector Scan, Variable Spaped Beam) • Analyze Write Performance **REACTIVE ION ETCH SUBSYSTEM** • Load/Unload • Control Process Gas Flow • Control RF Power • Perform Ion Etch **ION IMPLANT SUBSYSTEM** • Load/Unload • Control Process Gas Flow • Apply Precise Current to Ion Beam • Focus and Deflect Ion Beam • Activate Ion Source • Control Magnetic Setting • Analyze Implant Performance (Dose Processor, Oscilloscope, Uniformity) **SPUTTER SUBSYSTEM** • Load/Unload • Perform Sputter Process • Select and Index Targets • Measure Film Resistance (Eddy Current Monitor) **RAPID ISOTHERMAL ANNEALING SUBSYSTEM** • Load/Unload • Position Shutter • Control Radiant Thermal Energy **INSPECTION STATION SUBSYSTEM** • Load/Unload • Position Wafer • Compensate for Wafer Thickness, Flatness Variations • Perform Fine Alignment • Probe Wafer • Perform System Diagnostics	Listed process mechanizations represent terrestrial SOA capabilities. However, terrestrial mechanizations must be adapted to function in microgravity and high vacuum. Standardization of process hardware and software becomes a major challenge: • Process Control Software, Language • Cassette Handling (Load/Unload) Uniformity • Parts (Mechanical, Electrical) • Electrical Power

Figure 4.3-1 Automation Requirements Summary

Standardization becomes the key challenge to process mechanization. In the terrestrial setting, people provide the interface between subsystems, and there is little need for subsystem compatibility. However, the desired autonomy of space manufacturing requires standardization of process hardware and software for economic and logistic reasons. Process control language, compatibility, cassette load/unload uniformity, mechanical/electrical parts uniformity, and electrical power compatibility represent the major elements requiring a concerted standardization effort on the part of the subsystem manufacturers.

4.3.2 TELEOPERATION/ROBOTICS

Teleoperation and robotics will play key roles in the autonomous manufacture of integrated circuits in space. The conceptual design incorporates dual robot arms for cassette handling between process and inspection subsystems, and a dedicated maintenance teleoperator/robot. Figure 4.3-2 depicts the process transport and maintenance robot end effectors as designed for use aboard the chip manufacturing facility.

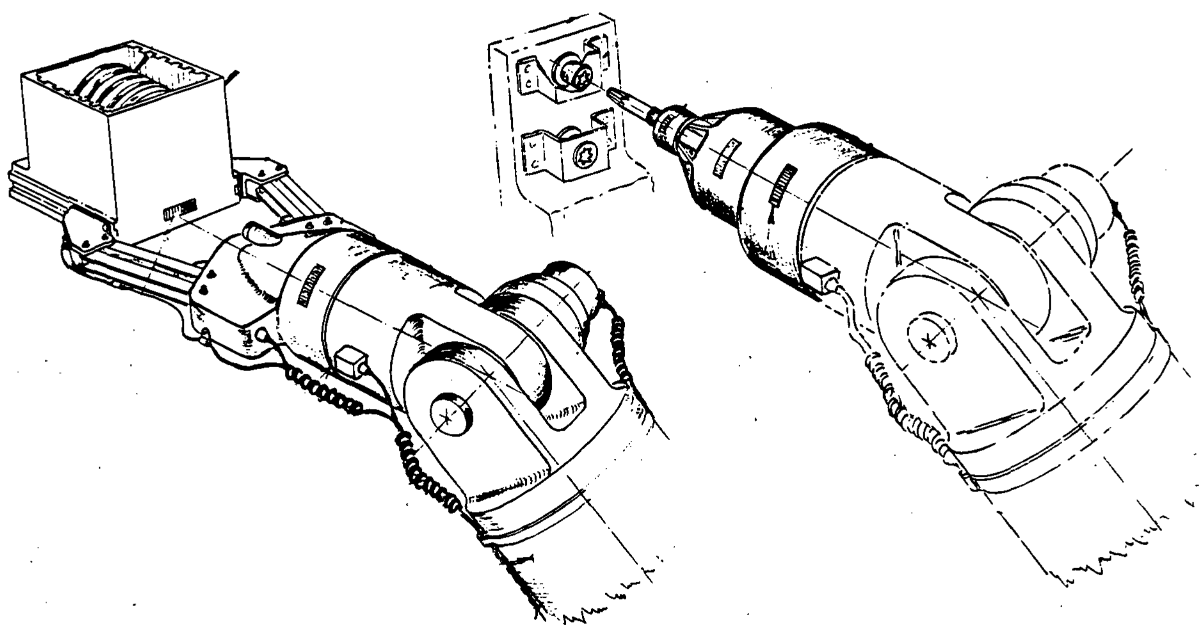

Figure 4.3-2 Process Transport and Maintenance Robot End Effectors

C-2

4.3.2.1 Process Transport Robots

Two adaptive robot arms located on separate tracks with zero-gravity traction capability, have been identified to serve as process transporters between the various process subsystems. Although hard automation would fulfill the cassette transport requirement, it is felt that the adaptive robots will add a dimension of functional flexibility to the facility. These same adaptive robot arms, equipped with vision and tactile sensors, can be used to perform scheduled preventative maintenance activities. Such activities include replacing filters, shields or parts before they wear out, and replenishing consumables such as sputter targets before they erode. In addition, these robot arms will serve as inspection transporters, removing random cassettes from various process stations as directed by EPiC, transporting the cassettes to the inspection station, and returning inspected cassettes to the appropriate process station. Robotic transport applications represent straight forward SOA capabilities, however, the technology for handling the light, moderately fragile cassettes in the space environment requires further development. Robot arms must be sensitive to the proximity of other arms and process station locations to ensure smooth cassette transport without collision.

4.3.2.2 Maintenance Teleoperator/Robot

Unscheduled maintenance activities in the form of minor and major repairs constitute the major automation challenge to the chip processing facility. As conceptualized, the maintenance automation scheme will evolve from a teleoperated system to an eventual fully automated maintenance robot. Although the facility module can be pressurized for shirt sleeves repair tasks by crewmen, this is to be avoided if at all possible. Every pressurization will be followed by a nonproductive contamination pump down period.

The initial concept calls for a dedicated maintenance robot arm to be controlled through telepresence in performing repairs and the more difficult preventative maintenance procedures. The teleoperated arm is controlled remotely using the feedback from the vision and tactile sensors. This hybrid robot is identical in function to the robot described in Section 3.3.2.

As enabling technologies evolve, and procedural programming ("training") of the maintenance robot occurs, more maintenance activities, including major repairs and servicing, can be performed automatically. Ultimately the role of telepresence will be reduced to emergency response, as the telepresence capability offers a highly desirable safety feature.

As summarized in Figure 4.3-1, the maintenance robot will be responsible for removing and replacing a variety of subsystem elements, (electronic cards, filters, shields, filaments, lenses, process materials, etc. and even other robot arm component modules) as well as the performance of repair, cleaning, and refurbishing functions. Significant development will be required to incorporate maximum hardware standardization, and to automate the maintenance, repair and servicing functions which are currently performed manually on earth. Standardization will minimize the total number of tools required for use by the robot. Maintenance tasking should be designed to minimize the number and length of robotic motion, and to minimize the force, accuracy, and repeatability requirements. According to SRI (Reference 1, pg. 11): "An accuracy of 3 mm in position and 2 degrees in orientation should accommodate most handling tasks in the facility with proper parts and tool design.

Similar to the robotic assessment in Section 3.3.2 the requirement for advanced control systems running flimsy arms with large masses has not been identified. Rather, the robots conceived for this facility are relatively slow and should be relatively stiff.

4.3.3 ARTIFICIAL INTELLIGENCE

AI is seen as an eventual requirement in two areas: process control and maintenance. The complexities of chip manufacturing, coupled with the inherent uncertainties associated with space manufacture, give rise to the need for an eventual integrated "expert" system. The proposed expert process and maintenance controllers offer a knowledge-base from which the Space Station operator can draw detailed explanations to implement timely process adjustments or maintenance functions.

The magnitude of the manufacturing facility warrants having dedicated process engineer(s) on board the Space Station with necessary ground support during start-up. Once on-line, the process complexities preclude any one individual from possessing the expertise necessary to detect all implicit processing deficiencies, or to correct all deficiencies once they have been identified. Economics preclude crew members from devoting time to lengthy trouble shooting endeavors. As is the case in any manufacturing scheme, process deficiencies and equipment down time stifle productivity and eat up profits. By implementing the proposed expert process and maintenance controllers, deficiencies and down time would be minimized.

The development of expert controllers to accommodate the host of variables associated with the manufacture of chips in space, will be an evolutionary process. Initially causal models can be developed to address the known terrestrial challenges and predicted space processing variables. As space processing anomalies are encountered, analyzed, and handled, the knowledge-base would expand. The controllers would evolve from a process "advisors" to fully automated intelligent controllers, capable of accommodating anomaly detection, isolation, and correction.

In theory the expert controllers serve as trouble shooting aids to the resident process engineer. The expert systems capture the combined knowledge-base of process and maintenance experts, and present the resulting expertise in a modular, upgradable structure. This rule-based structure would consist of a domain of expertise (knowledge-base) and a mechanism (inference engine) for interpreting this expertise. The expertise can be further divided into <u>facts</u> surrounding a given process subsystem, or maintenance function, and heuristics or <u>rules</u> which control the use of knowledge-base in solving the problem.

The inference engine serves as an interpreter of the facts and rules. Facts are initially generated by asking the process engineer a fixed set of questions. As the expert system evolves, facts will be generated through system inference. Rules are conditioned statements consisting of a situation recognition part (premise) and an action part (conclusion). The inference engine monitors the facts in the data base, and executes the action part of those rules that have been satisfied. Figure 4.3-3 represents the proposed expert trouble shooting architecture, as it evaluates a typical process deficiency i.e., low reflected energy after sulfur implantation. A fixed sequence of questions is used to gather initial facts surrounding the process deficiency, including process station performance and reported anomalies. The associated properties table provides additional facts such as process equipment features, process parameters, history of process deficiencies, and process failure propensity. These combined inputs constitute the facts to be interpreted by the inference engine using developed hypotheses and rules. The interpretation results in a final diagnosis and a detailed corrective action plan.

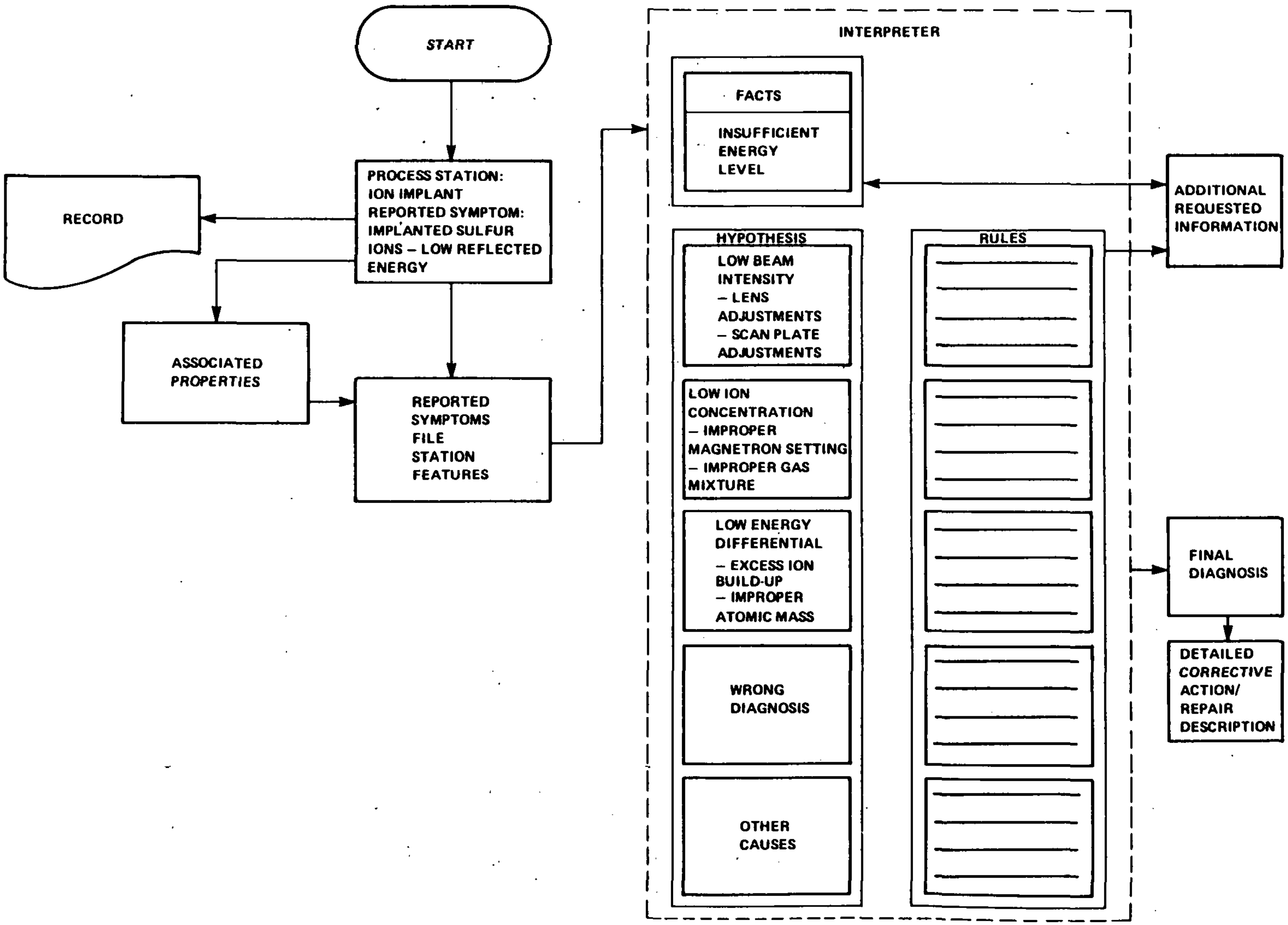

Figure 4.3-3 Proposed Expert Trouble Shooting Architecture

4.3.3.1 Expert Process Controller (EPiC)

To develop an effective expert system to serve as a process controller, one must understand the process mechanisms which promote low yield and poor device reliability. Ideally, in a properly fabricated GaAs wafer, one would expect all chips on the wafer to be good functional circuits. In actuality, yield is significantly less than ideal, with causes for less-than-perfect yield falling into three categories: 1) processing problems, 2) design problems, and 3) random point defects.

1) Process Failures

The analysis of a finished wafer typically reveals the polarization of "good" chip regions and "bad" chip regions. Processing effects which lead to the existence of low yield regions can include: variations in the thickness of deposited layers; variations in the lithographically defined features; and variations in the registration of a photomask. The majority of associated variables are interdependent. Deposited layers which are thinner than average become over-etched when the wafer is etched for the specified time period. Gates are shorter in the thinner regions, often resulting in channel lengths which preclude the transistors from being turned off when appropriate gate voltages are applied. Thus, the chips may experience excessive leakage current, or may not function at all.

Variations in the doping of implanted layers can result in variations in contact resistance. Similarly, variations in the thickness of the deposited dielectric can result in contact window size variations. Both resulting variations often lead to defective chips, particularly when the chip contains circuits whose performance is dependent upon having a low contact resistance value.

During processing, the wafer undergoes a series of operations which result in small, but critical changes in wafer dimensions. It is not uncommon for wafer size to vary in excess of desired alignment tolerances. Therefore, size variations must be compensated for in order to prevent misalignment. In addition to size variation, stacking faults often occur when improper cleaning techniques leave chemical residues. The resulting oxidation, again, leads to excessive leakage current and circuit failure.

2) Chip Failures

The second yield limiting category which offers potential for AI application, involves chip design. Areas of the wafer may reflect low yields because the design of the circuit failed to account for expected variations in device parameters. Threshold voltage and channel length are two such parameters whose variations require detailed consideration during chip design. Variations in substrate doping, gate oxide thickness, and ion implant dosage will cause variations in the threshold voltage. Channel length varies with respect to gate length, and source and drain junction depth and ultimately determines circuit speed. Chip design must also consider variations in other device parameters, including: the resistance of implanted region, capacitance of conductors, contact resistance, and leakage current.

Two chips with nominally the same size and complexity, processed identically, can have vastly different yields. The higher yield is the result of a cooperative effort between the circuit designer, who identifies the specific device parameters and processing idiosyncrasies to which the chip design must be sensitive, and the process engineer (EPiC) who optimizes both the value and range of variation of those

parameters. With EPiC assimilating process sensitivities, design changes could be implemented by reprogramming the E'beam Direct Write to generate EPiC pattern alterations. The dynamic design capability would promote still higher yield and lower defective costs.

3) Point Defects

The third cause of less-than-perfect yield is attributed to random point defects. A point defect is defined as a small region of the wafer where the processing is imperfect. There are many types of processing defects defined as point defects, the most common being dust or similar contaminants. These particles can be introduced during wafer transport between process stations, be incorporated in the films being deposited, or be present in photo resist solutions. Random oxidation, induced stacking faults, isolated spikes in an epitaxial film, or pinholes in a dielectric film can also result in point defects.

Point defects often occur on lithographic masks as well. Particles adhering to the mask during use cause a gradual increase in the density of point defects reproduced on the wafer, requiring unscheduled cleaning of the mask.

In meeting the three process challenges described above, the successful manufacture of GaAs chips in space requires responsive process QA control system. The electrical, mechanical, and optical monitors used to evaluate the various process steps, should ultimately be linked to the expert process controller (EPiC). Quality control should be maintained through the real-time interface between the process monitors and EPiC.

Much of the detailed in line inspection performed during terrestrial fabrication will, of necessity, be eliminated from the space fabrication process. Physical dimensions preclude the inspection stations associated with each process station. For this reason, an expert process controller (EPiC) with a substantial knowledge base, is needed to orchestrate the highly complex process analysis and defect handling tasks. Random cassettes are selected by EPiC, removed from the process chain by robot arm, and loaded into the centralized inspection station. Wafers are selected at random by EPiC, analyzed, and returned to the cassette. Cassettes will then be returned to the process chain by the robot arm for continuation of processing. If defects are noted during inspection, the entire cassette can be analyzed for defect repeatability. Defect trending and analysis information is assimilated by EPiC, with the nature and density of defects triggering appropriate action from the controller, should process adjustments be required.

4.3.3.2 Expert Maintenance Controller

The high level of sophistication associated with the subsystem equipment requires considerable monitoring and control. As specific on-line data is received from the various equipment monitors, the expert system interprets the data and generates appropriate flags when subsystem anomalies are encountered. As the expert system evolves, it will implement routine equipment checks, interpret deviancies, and initiate corrective action prior to hard failure.

Although it can be assumed that there will be a dedicated technician on board, it is unlikely that such a crew member would possess the expertise necessary to recognize and diagnose dynamic maintenance problems, and then determine the best course of corrective action for each of the subsystems. In the initial implementation of the maintenance controller, the expert system would serve in an advisory capacity, interpreting and flagging equipment and servicing anomalies, and providing detailed repair and servicing procedures to the technicians for handling. In time as faults are detected, isolated, and handled, the expert system can be programmed to take on increasing responsibility in implementing corrective action. The ultimate maintenance concept embraces an "intelligent robot" scheme which would further reduce man's role to a supervisory level with occasional teleoperated intervention. The maintenance applications addressed in Section 4.3.2.2 provide insight into the type of data needed for incorporation into the expert's knowledge-base.

5.Ø CONCLUSIONS

The two manufacturing concepts developed in this study are representative of innovative, technologically advanced manufacturing schemes. The concepts were selected to facilitate an in-depth analysis of manufacturing automation requirements in the form of process mechanization, teleoperation and robotics, sensors and artificial intelligence. While the cost-effectiveness of these facilities has not been analyzed as part of this study, both appear entirely feasible for the year 2ØØØ timeframe. The growing demand for high quality gallium arsenide microelectronics may warrant the ventures.

The evolution of enabling technologies for space manufacturing will require detailed planning, and coordination with the design team. To facilitate the generation of a responsive automation plan, a list of Generic Space Manufacturing Activities was developed from the McDonnell Douglas Generic Space Activities list (see THURIS Report for activity definitions). This list, as it appears in Figure 5.Ø-1, was further developed to reflect the degree of automation and associated technology requirements necessary to perform each of the activities over four time phased periods. The figure accurately represents the intimate involvement of man in the process loop at IOC, and the subsequent scaling down of man's role with time to accommodate the ultimate autonomous concept.

Figure 5.Ø-2 depicts the evolution of automation technologies for space manufacturing from initial development studies, through IOC, to the ultimate autonomous manufacturing facility. This technological progression enhances the stated Space Station technology goals of "maintainability, autonomy, long life, human productivity, evolution, and low life-cycle costs".

GENERIC SPACE MANUFACTURING ACTIVITIES	1992 – 1995		1996 – 2000		2001 – 2005		2006 – 2010	
	DEGREES OF AUTOMATION	ENABLING TECHNOLOGIES	DEGREES OF AUTOMATION	ENABLING TECHNOLOGIES	DEGREES OF AUTOMATION	ENABLING TECHNOLOGIES	DEGREES OF AUTOMATION	ENABLING TECHNOLOGIES
ACTIVATE/INITIATE MANUFACTURING PROCESS	MAN	SWA	TELOP	TELEPR	AR	AI	IR	EXP
ADJUST/ALIGN ELEMENTS	MAN, TELOP, HA	TELEPR, SWA	TELOP, HA	TELEPR, SWA	AR	AI, VTS, 3DI	IR	AI, VTS, 3DI
ALLOCATE/ASSIGN/DISTRIBUTE RESOURCES	MAN, HA	SWA	TELOP, HA, PR	TELPR	AR	AI, VTS	IR	EXP, VTS
APPLY/REMOVE SENSORS	TELOP, HA	TELEPR, SWA	HA, VR	SWA	HA, AR	SWA, AI, VTS	HA, IR	EXP, VTS
COMMUNICATE INFORMATION	MAN, TELOP, HA	TELEPR, SWA	HA	SWA	HA	SWA	HA	SWA
COMPENSATORY TRACKING	MAN, TELOP, HA	TELPR, SWA	HA	SWA	AR	AI	IR	EXP
COMPUTE PROCESS DATA	HA	SWA	HA	SWA	AR	AI	IR	EXP
CONFIRM/VERIFY PROCEDURES/SCHEDULES/OPERATIONS	MAN, HA	SWA	HA	SWA	HA, AR	AI	HA, IR	EXP
CONTROL ELECTRICAL INTERFACE	MAN, HA	SWA	HA	SWA	HA, AR	AI	HA, IR	EXP
CONTROL FLUID/GAS INTERFACE	MAN, HA	SWA	HA	SWA	HA, AR	AI	HA, IR	EXP
CORRELATE PROCESS DATA	MAN, HA	SWA	HA	SWA	AR	AI	IR	EXP
DEACTIVATE/TERMINATE MANUFACTURING PROCESS	MAN	SWA	TELOP	TELEPR	AR	AI	IR	EXP
DECODE/ENCODE DATA	HA	SWA	HA	SWA	HA	SWA	HA	SWA
DEFINE PROCEDURES/SCHEDULES/OPERATIONS	MAN, HA	SWA	MAN, HA	SWA	AR	AI	IR	EXP
DEPLOY/RETRACT ROBOT ARM	TELOP, HA	TELEPR, SWA	TELOP, HA	TELEPR, SWA	AR	AI	IR	AI
DETECT CHANGE IN STATE OR CONDITION	MAN, HA	SWA	HA	SWA	AR	AI, VTS	IR	EXP, VTS
DISPLAY DATA	TELOP, HA	TELEPR, SWA	HA	HA	HA, AR	AI, VTS	HA, IR	AI, VTS
GATHER/REPLACE TOOLS/EQUIPMENT	MAN, TELOP	TELEPR	TELOP, AR	TELEPR	AR	AI, VTS, 3DI	IR	EXP, VTS, 3DI
HANDLE/INSPECT/EXAMINE PRODUCT	MAN, TELOP	TELEPR	TELOP, AR	TELEPR	AR	AI, VTS, 3DI	IR	EXP, VTS, 3DI
IMPLEMENT PROCEDURES/SCHEDULES	MAN, TELOP, HA	TELEPR, SWA	HA, VR	SWA	AR	AI, VTS	IR	EXP, VTS
INFORMATION PROCESSING	MAN, HA	SWA	HA	SWA	HA, AR	AI	IR	EXP
INSPECT/MONITOR	MAN, TELOP, HA	TELEPR, SWA	TELOP, HA, AR	TELEPR, SWA	HA, AR	AI, VTS, 3DI	HA, IR	EXP, VTS, 3DI
MEASURE PRODUCT DIMENSIONS	MAN, TELOP, HA	TELEPR, SWA	TELOP, AR	TELEPR	AR	AI, VTS	IR	AI, VTS
PLOT DATA	MAN, HA	SWA	HA	SWA	HA	SWA	HA	SWA
POSITION COMPONENT	MAN, TELOP, HA	TELEPR, SWA	TELOP, HA, AR	TELEPR, SWA	HA, AR	AI, VTS, 3DI	IR	AI, VTS, 3DI
PRECISION MANIPULATION OF OBJECTS	MAN, TELOP	TELEPR	TELOP, AR	TELEPR	AR	AI, VTS, 3DI	IR	AI, VTS, 3DI
PROBLEM SOLVING/DECISION MAKING/DATA ANALYSIS	MAN, HA	SWA	MAN, HA	SWA	MAN, HA	AI	IR	EXP
PURSUIT TRACKING	MAN	SWA	HA, AR	SWA	HA, AR	AI, VTS	IR	EXP, VTS
RELEASE/SECURE MECHANICAL INTERFACE	MAN, TELOP	TELEPR	TELOP, AR	TELEPR	AR	AI, VTS	IR	AI, VTS
REMOVE COMPONENT	MAN, TELOP, HA	TELEPR, SWA	TELOP, AR	TELEPR	AR	AI, VTS, 3DI	IR	EXP, VTS, 3DI
REMOVE/REPLACE COVERING	MAN, TELOP	TELEPR	TELOP, AR	TELEPR	AR	AI, VTS	IR	AI, VTS
REPLACE/CLEAN SURFACE COATINGS	MAN, TELOP	TELEPR	TELOP, AR	TELEPR	AR	AI, VTS	IR	AI, VTS
REPLENISH MATERIALS	MAN, TELOP	TELEPR	TELOP, PR	TELEPR	AR	AI, VTS	IR	EXP, VTS
STORE/RECORD ELEMENTS	MAN, TELOP, HA	TELEPR, SWA	TELOP, HA, AR	TELEPR	AR	AI, VTS	IR	AI, VTS
TRANSPORT ELEMENTS	MAN, TELOP, DR	TELEPR	AR	AI	AR	AI, VTS	IR	AI, VTS

DEGREES OF AUTOMATION		ENABLING TECHNOLOGIES	
• MAN	– MANUAL	• SWA	– SOFTWARE ALGORITHM
• TELOP	– TELEOPERATION	• TELEPR	– TELEPRESENCE
• HA	– HARD AUTOMATION	• VTS	– VISUAL-TACTILE SENSOR
• UR	– UNADAPTIVE ROBOT	• 3DI	– 3-DIMENSIONAL IMAGING
• AR	– ADAPTIVE ROBOT	• AI	– ARTIFICIAL INTELLIGENCE
• IR	– INTELLIGENT ROBOT	• EXP	– EXPERT SYSTEM

Figure 5.0-1 Time-Phased Automation Requirements For Space Manufacturing Activities

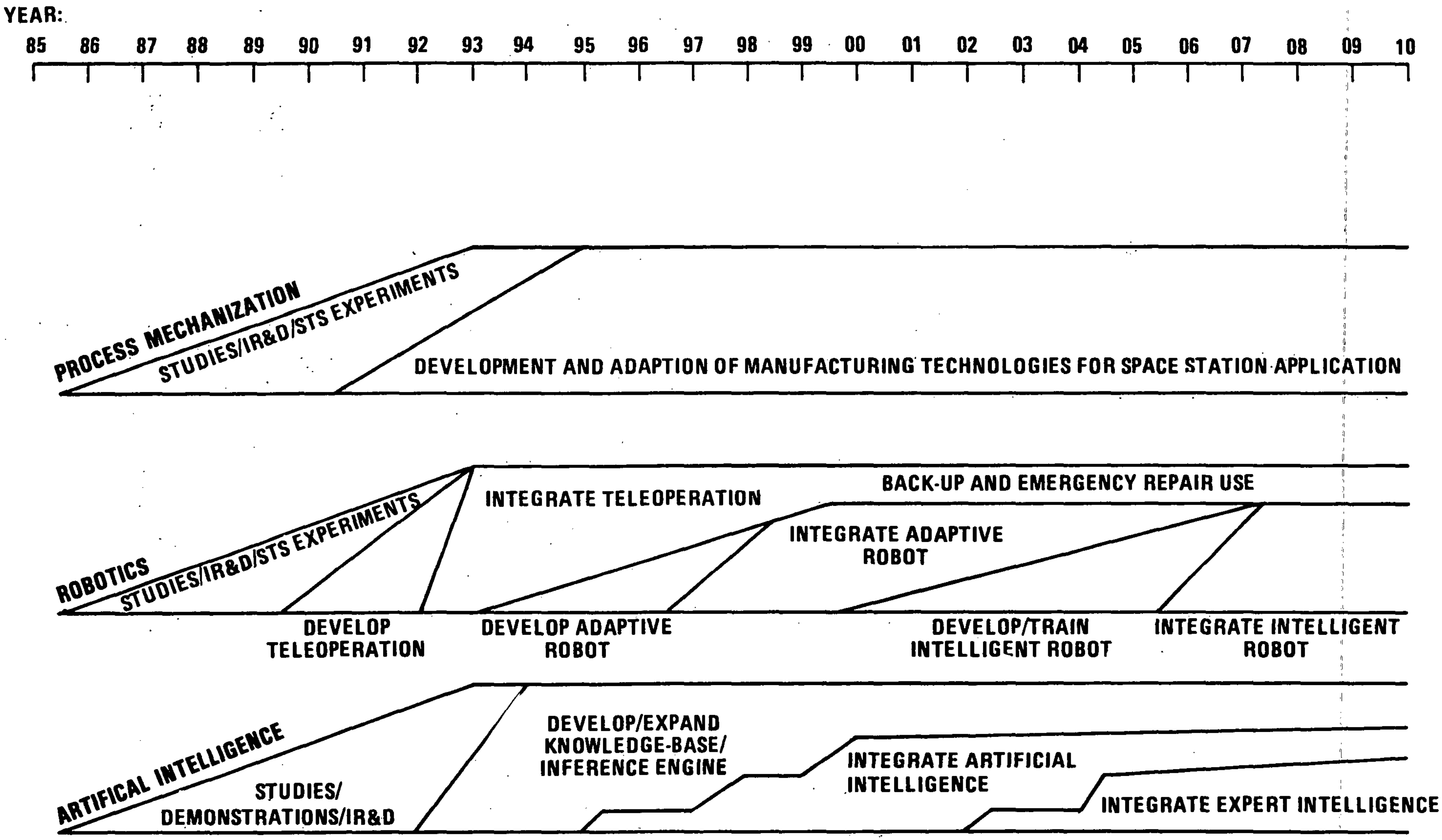

FIGURE 5.0-2 Evolution of Automation Technologies for Space Manufacturing

Additional work must be accomplished to develop highly automated facilities such as those described beyond the conceptual stage. Such automated equipment is essential for cost-effective space manufacturing. The equipment must be packaged more compactly than shown in this report. It must be space qualified and highly reliable, and must eventually be capable of much self-repair.

Very versatile industrial robots are in extensive use today. Those conceptualized for use in space will be of a very different design. They must be able to operate in a hostile environment of hard vacuum with potentially high thermal gradients and radiation. While microgravity allows their design to be lightweight, different kinematics and dynamics will exist. Different approaches to actuation devices and end-effectors must therefore be developed. While the lack of gravity reduces grip and wrist forces, gravity can no longer be used as a helper to catch things or hold them in place. Since the robots must be versatile enough to handle different materials and various repair and maintenance functions, a quick change end-effector replacement system will be required. Many of the complex maintenance and repair functions will be initially done by teleoperators; therefore, feedback devices, including visual and tactile sensors, must be developed well beyond todays designs.

As more autonomy is developed, the more reliable, serviceable, easily repairable, and accurate the equipment must be. It will be difficult to provide the space station crew the kind of access, information and resources needed to adjust or repair highly automated systems in the confines of a space facility to the degree possible in an earth-base factory.

The major challenge of space manufacturing is maintenance and repairs. Without the automation capabilities to accomplish these functions, manufacturing in space of items in large production lots will be unattainable.

Artificial Intelligence can be developed for manufacturing facilities which will provide efficient control of troubleshooting, maintenance and corrective action options. Development of "expert systems" to do the job even better must await expertise to be gained in operating the system during development and in space. This means any program must walk before running by initially providing crew easy access to hardware and "user friendly" software where possible. As experience is developed, more hardware and software automation can be accomplished, thus making space factories more productive by trading access space for more equipment and materials storage. The space crew will contribute much to this evolution, and will supply much of the expertise needed to develop expert systems for maintenance and repair automation.

Expert systems are very difficult to develop. A data base must be developed and expanded as a facility matures. Therefore *more human involvement will be required early in the evolution of* each facility. Elements of an expert system can be developed individually, but need to be structured to fit effectively into the total system as it evolves.

Space manufacturing activities must be closely coordinated with other Space Station activities. Impact assessments need to be conducted during Phase B studies to ensure compatibility of manufacturing missions with Space Station operations. As an example, the Space Station data handling system will need to include sufficient levels of language, capacities, and rates to accommodate the desired manufacturing data. A GE-JPL working meeting produced the projected data handling requirements shown in Figure 5.0-3, for the wafer manufacturing and chip production schemes for both an IOC and ultimate configuration. Projected data handling capacities and rates should prove helpful in designing a data management system with sufficient scarring to accommodate an evolving Space Station manufacturing facility.

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OF POOR QUALITY

CONCEPTS	DRIVERS	IOC 1995/2000													
		SOFTWARE		LEVEL OF INTELLIGENCE				COMMAND RATE		DATA RATE		MEMORY CAPACITY		PROCESS RATE	REMARKS
		LINES OF CODE	LEVEL OF LANGUAGE	HARD CONTROL	S/W ALGORITHM	A.I.	CREW MEMBER	GROUND	SS	GROUND	SS	DATA BASE	PROCESS DATA		
GaAs ELECTROEPITAXIAL WAFER MANUFACTURE	DATA MANAGEMENT SYSTEM	MED.	HOL		X		MAINT. SS INTERFACE	300 K BITS	1 MBIT	10 MBIT	20 MBIT	20-30 MBYTES	10 MBYTES	5 MOPS	OCCASIONAL TV UPLINK FAULT TOLERANT
	ROBOT SYSTEM	MED.	HOL		X		TELEOPERATED FOR MAINT.	NONE	1 MBIT	10 KBIT	20 MBIT	1 MBYTE	500 KBYTES	1 MOP	TELEOPERATION, COORDINATE TRANSFORMATIONS
	PROCESS CONTROLLER	10-15K	HOL		X		MONITOR & DATA RETURN	<1 KBIT	<1 KBIT	1 MBIT ON DEMAND VIDEO	5 MBIT VIDEO	1 MBYTE	500 KBYTES	10 KOPS	MINI-COMPUTER
	SYSTEM SCHEDULER	MED.	HOL		X	X	S.S. INTERFACE	4 KB	8 KB	4 KB	8 KB	1 MBYTE	1 MBYTE	1 MOP	
GaAs MICROELECTRONIC CHIP PRODUCTION	DATA MANAGEMENT SYS.	HIGH	HOL		X		CONTROL	50 KB	1 MB	5 MB	15 MB	1 GBYTE	1 MBYTE	5 MOPS	PARALLEL PROCESS FAULT TOLERANT DISTRIBUTED CONT.
	ROBOT SYSTEM	LOW	HOL	X	X		MAINT.	<1 KBIT	1 MBIT	<1 KBIT	20 MBIT	10-20 MBYTE	1 MBYTE	2 MOPS	MAINT.- TELEOPERATED PROCESS-AUTOMATIC
	PROCESS CONTROLLER	HIGH	V HOL	X	X	LOW-END A.I.	MONITOR PROCESS DECISIONS	50 KB	1 MBIT	5 MBIT	15 MBIT	1-2 GBYTE	10 MBYTE	5 MOPS	VIDEO TO SS/GRND HI CREW INTERACTION QA
	MAINTENANCE CONTROLLER	HIGH	HOL	X	X			<1 KBIT	1 MBIT	<1 KBIT	15 MBIT	1 GBYTE	1 MBYTE	5 MOPS	MC IS ADVISOR CREW DOES MAINT.-TELOP.

CONCEPTS	DRIVERS	ULTIMATE CONCEPT 2000S+													
		SOFTWARE		LEVEL OF INTELLIGENCE				COMMAND RATE		DATA RATE		MEMORY CAPACITY		PROCESS RATE	REMARKS
		LINES OF CODE	LEVEL OF LANGUAGE	HARD CONTROL	S/W ALGORITHM	A.I.	CREW MEMBER	GROUND	SS	GROUND	SS	DATA BASE	PROCESS DATA		
GaAs ELECTROEPITAXIAL WAFER MANUFACTURE	DATA MANAGEMENT SYSTEM	DECREASE WITH EVOLUTION	V HOL			EXPERT	MINIMAL	<1 KB	1 KB	<1 KB	<1 KB	1 GBYTES	1 MBYTE	10 MOPS	PATTERN RECOGNITION EXPERT
	ROBOT SYSTEM	PROGRAM BY DMS	HOL		X	EXPERT PATTERN RECOGN.	TELEOP. BACKUP	0	0	0	0	10-20 MBYTE	500 KBYTES	2 MOPS	
	PROCESS CONTROLLER														BURIED IN DMS
	SYSTEM SCHEDULER														BURIED IN DMS
GaAs MICROELECTRONIC CHIP PRODUCTION	DATA MANAGEMENT SYS.	LOW	HOL		X	ADAPTIVE	NONE	<1 KBIT	1 MBIT	<1 KBIT	1 MBIT	1 GBYTE	1 MBYTE	20 MOPS	PARELLEL, DISTRIBUTED FAULT TOLERANT
	ROBOT SYSTEM		HOL		X	EXPERT ADAPTIVE	TELEOP. BACKUP	0	0	0	0	20-40 MBYTES	1 MBYTE	4 MOPS	
	PROCESS CONTROLLER	HIGH	V HOL	X	X	EXPERT ADAPTIVE	NONE	<1 KBIT	1 KBIT	<1 KBIT	1 KBIT	10 GBYTES	10 MBYTES	10 MOPS	EPIC; PARALLEL PROCESSING
	MAINTENANCE CONTROLLER	HIGH	V HOL		X	EXPERT ADAPTIVE	CONSULT FOR MAJOR REPAIRS	<1 KBIT	<1 KBIT	<1 KBIT	<1 KBIT	10 GBYTES	10 MBYTES	5 MOPS	SERIAL MAINTENANCE

Figure 5.0-3 Estimations of Data Handling Requirements For Space Manufacturing Concepts

Other Space Station manufacturing interfaces that have been identified as requiring further evaluation by Phase B contractors include power, thermal, servicing and waste management.

- <u>Power</u> - Further study to determine power distribution impacts on process scheduling; scarring study to accommodate power expansion requirements beyond IOC, assessment for potential of using GaAs crystal growth process to manufacture additional solar arrays to create additional/independent power sources.

- <u>Thermal</u> - Study to assess the effects of thermal shadowing on the manufacturing process; trade-study to evaluate centralized vs distributed control of temperatures; assessment of the economics of capturing Space Station waste head energy or solar energy to help drive furnaces.

- <u>Servicing</u> - Study to assess Universal Space Station approach for raw materials and gas handling; study to determine problems associated with handling toxic materials/gases.

- <u>Waste Management</u> -Study to resolve waste collection vs dumping trade-offs; evaluation of a common waste collection module to be launched from the Space Station for incineration by the sun.

6.0 RECOMMENDATIONS

We must "get on with the show": to do so means that research and development must be accomplished in many areas and certain space hardware developed and proven.

The following five specific programs are recommended as a result of this study; they are believed to be essential for many other space manufacturing applications as well.

(1) Space Manufacturing Concepts Development Study
Several manufacturing design concepts, including those described in this report, would be more fully developed to define system requirements, preliminary facility and automation designs, maintenance and repair scenarios, space station interfaces, cost-effectiveness, and evolutionary growth of each through a twenty year period. The concepts would be chosen to assure maximum applicability for automation of manufacturing processes and associated maintenance and repair for all potential space manufacturing applications.

(2) Space Robotics System Experiment
A general purpose, hybrid robot would be designed for experimental evaluation in space. A hybrid robot normally operates under program control with sensory feedback, but for certain applications can be remotely controlled as a teleoperator. A modular design will be considered, so that combinations of different configurations can be evaluated. Self maintainability, the capability of one robot to perform maintenance, repair, and servicing as required for itself or for another robot, will be explored.

Performance and design requirements would be determined using the Space Manufacturing Concepts Development Study as the primary reference, and reviewed by an independent industrial/university committee. After approval, the design would be fully developed, and an experimental robot, together with its controller and a variety of sensor systems, actuators, tools and end-effectors manufactured, tested and flown as experiments on the Shuttle by 1990. Experiments would concentrate on maintenance and repair activities, but also investigate materials handling tasks.

(3) Materials Management Study

Space-based handling of the various raw materials required for space manufacturing, and the handling and disposal of waste products and by-products would be studied. Gaseous, liquid and solid waste products would be included and concepts developed for handling of hazardous, valuable and unstable materials in the space environment. Servicing schemes for replenishment and disposal would also be addressed.

(4) Materials Handling Experiments

Experiments in materials handling which are necessary for a variety of manufacturing applications would be flown on shuttle in the 1989-1991 time frame. Included would be experiments in gaseous, liquid, and solids handling of raw and waste materials and by-products, selected from results of the Materials Management Study. Handling of toxic materials necessary for likely space manufacturing systems and collection of dust-like particles resulting from slicing and polishing operations would be candidate experiments. Some experiments would be integrated with the Space Robotics System Experiment.

(5) Space Manufacturing Artificial Intelligence Applications Study

A university/industry team would study specific concepts selected from the Space Manufacturing Design Concepts Development Study to define conceptual artificial intelligence system designs for control, maintenance, troubleshooting, and corrective actions required to operate the facilities. The data management system requirements for these AI concepts would be sized and interfaces with the Space Station Data Management System (DMS) defined thus providing the foundation for full development of Space Manufacturing AI applications. This effort should commence as soon as possible because of the potential impact on Space Station DMS architecture.

Figure 6.Ø-1 shows the recommended timeline and interrelationships of these recommended activities, as well as estimates of costs and study contractor recommendations.

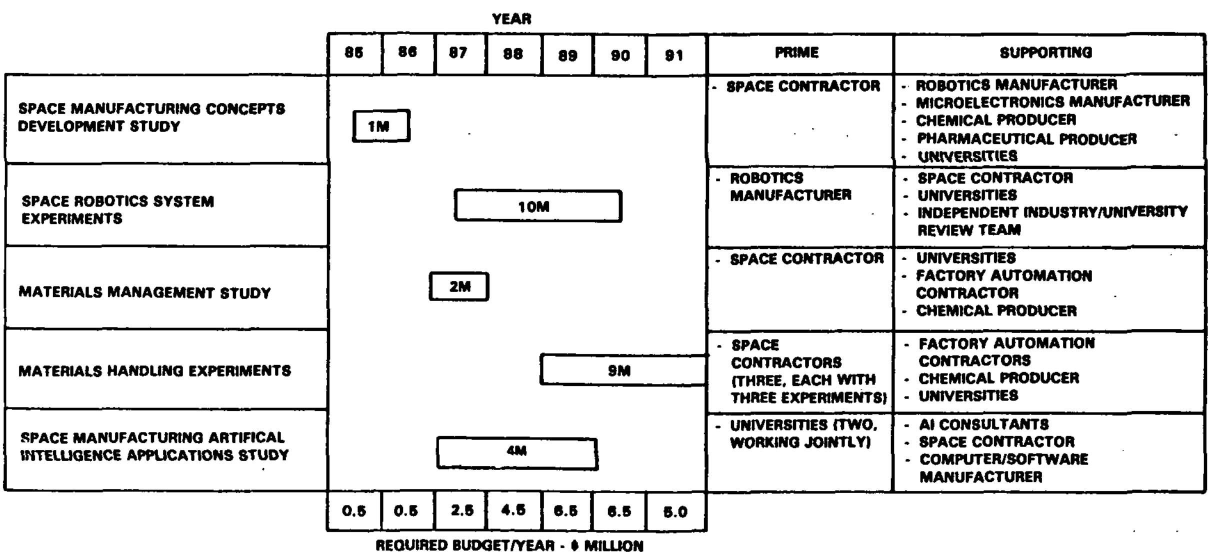

Figure 6.Ø-1 Timeline Of Recommended Space Station Automation Development Studies

These studies and experiments will develop new technologies required for space manufacturing. The studies will also stimulate interest in the manufacturing industries through involvement and understanding of the benefits of manufacturing in space. With the desire of American and foreign industries to reap these established benefits, the future of the Space Station Program will be assured.

STATEMENT OF WORK FOR
STUDY OF AUTOMATION OF REMOTE SPACE OPERATIONS

THIS STUDY WILL CONTRIBUTE TO A SPACE STATION AUTOMATION PLAN. THE PLAN WILL BE USED IN THE FOLLOWING FASHION:

- o THE PLAN WILL BE GIVEN TO THE AEROSPACE CONTRACTORS THAT WILL BE SELECTED TO PERFORM THE DEFINITION CONTRACTS. THE CONTRACTORS WILL BE GUIDED BY THE PLAN IN FORMULATING THE SPACE STATION CONCEPTUAL DESIGN.

- o THE PLAN WILL BE USED BY NASA'S OFFICE OF AERONAUTICS AND SPACE TECHNOLOGY AS AN INPUT TO THE PLANNING FOR ADVANCED TECHNOLOGY ENDEAVORS IN ROBOTICS, EXPERT SYSTEMS AND ARTIFICIAL INTELLIGENCE.

CALIFORNIA SPACE INSTITUTE WILL BE RESPONSIBLE FOR THE DEVELOPMENT OF THE SPACE STATION AUTOMATION PLAN. THE STANFORD RESEARCH INSTITUTE WILL HAVE THE RESPONSIBILITY TO PERFORM THE TECHNOLOGY EVALUATION AND TECHNOLOGY FORECASTING. THE PRIMARY PRODUCTS FROM THE STANFORD RESEARCH INSTITUTE WILL BE: IDENTIFICATION OF AREAS THAT ARE NOW TARGETED FOR AUTOMATION. ROBOTICS, A/I ETC; IDENTIFICATION OF ADDITIONAL AREAS FEASIBLE FOR AUTOMATION, ETC; PREDICTION OF WHEN CRITICAL TECHNOLOGIES WILL BE AVAILABLE; AND THE RISKS, COSTS AND PROGRAM BENEFITS ASSOCIATED WITH BRINGING THESE TECHNOLOGIES ON LINE.

THE CONTRACTOR WILL HAVE THE RESPONSIBILITY FOR THE STUDY OF AUTOMATION OF REMOTE SPACE OPERATIONS. THIS SYSTEM DESIGN EFFORT SHALL RESULT IN THE DELINEATION OF THE DESIGN CONSEQUENCES OF VARIOUS AUTOMATION STRATEGIES. THEREFORE, THE CONTRACTOR WILL WORK CLOSELY WITH NASA, CALIFORNIA SPACE INSTITUTE AND STANFORD RESEARCH INSTITUTE IN THE PERFORMANCE OF THIS STUDY.

THE CONTRACT SUPPORTS AN EFFORT TO DEFINE THE SYSTEM LEVEL APPLICATION OF AUTOMATION TECHNOLOGY FOR REMOTE SPACE OPERATIONS ASSOCIATED WITH SPACE STATION AND UNMANNED PLATFORMS. THE CONTRACTOR SHALL REVIEW PROPOSED REMOTE SPACE OPERATIONS INCLUDING INSPECTION, SCIENTIFIC OBSERVATIONS AND EXPERIMENTS, AND MANUFACTURING. THE CONTRACTOR SHALL DEFINE THE CURRENT METHODOLOGIES AND OPERATIONS REQUIRED FOR THESE REMOTE SPACE OPERATIONS, ASSESS THE INCREASED OPERATIONAL CAPABILITIES RESULTING FROM THE APPLICATION OF ADVANCES IN AUTOMATION TECHNOLOGY, AND PROPOSE AN APPROACH FOR THE PROGRESSIVE INTRODUCTION OF THIS TECHNOLOGY AS IT BECOMES AVAILABLE.

UNDER THIS CONTRACT, THE CONTRACTOR SHALL:

1. REVIEW PRIOR STUDIES AND CURRENT CONCEPTS FOR ESTABLISHING, OPERATING, MODIFYING, AND MAINTAINING REMOTE OPERATIONS.

2. SUMMARIZE THE TASKS REQUIRED FOR THESE REMOTE OPERATIONS. THE TASKS STUDIED SHALL INCLUDE, BUT NOT BE LIMITED TO:

A. INSPECTION

B. SCIENTIFIC OBSERVATION

C. REPLENISHMENT OF EXPENDABLES

D. EXPERIMENTS
1. INSTALLATION
2. OBSERVATION
3. MODIFICATION
4. DATA RECORDING, ANALYSIS, TRANSMITTAL

E. MANUFACTURING
1. OBSERVATION AND QUALITY CONTROL
2. FAULT DETECTION, ERROR ANALYSIS, AND CONTINGENCY PLANNING
3. REPAIR
4. MODIFICATION
5. LOGISTICS INCLUDING RAW PRODUCTS DELIVERY, FINISHED PRODUCT SHIPMENT AND BY-PRODUCTS OR SCRAP DISPOSAL

3. AFTER CONSULTATION WITH NASA, THE CONTRACTOR SHALL CONCENTRATE ON SELECTED TASKS TO:

A. ASSESS AREAS FOR POTENTIAL APPLICATION OF ADVANCED AUTOMATION

B. DEFINE INCREASED OPERATIONAL CAPABILITIES RESULTING FROM THE APPLICATION OF THIS TECHNOLOGY

C. DEFINE MAN'S ROLE IN THE AUTOMATED OPERATIONS

4. FOR THE SELECTED TASKS, THE CONTRACTOR SHALL PREPARE A TIME PHASED PLAN FOR INCREASING THE AUTOMATION LEVEL OF THE REMOTE OPERATION AS THE TECHNOLOGIES BECOME AVAILABLE.

THE CONTRACT PERIOD OF PERFORMANCE SHALL BE 9 MONTHS. THE TECHNICAL WORK WILL BE COMPLETED IN THE FIRST 4 MONTHS RESULTING IN AN ORAL PRESENTATION OF RESULTS. A FINAL REPORT SHALL BE PREPARED FOR REVIEW BY THE END OF 6 MONTHS. THE STUDY WILL REMAIN OPEN AND THE TECHNICAL PERSONNEL AVAILABLE FOR REVIEW AND INTERACTION WITH STANFORD RESEARCH INSTITUTE AND THE CALIFORNIA SPACE INSTITUTE TO ASSIST THEM IN THE PREPARATION OF THEIR RESPECTIVE REPORTS ON THE PROJECT.

DEFINITIONS

AUTONOMY

Autonomy is an attribute of a system/subsystem that will allow it to operate within its specified performance requirements as an independent unit or element without external intervention (for a specified period of time.) Note:some people don't like the time constraint.

AUTOMATION

Automation is the use of machines to effect initiation, control, modification, or termination of system/subsystem processes in a predefined or modeled set of circumstances. The implication is that little or no further human intervention is needed in performing the operation. The terms "hard automation" and "flexible" automation define subsets of automation.

TELEOPERATION ("REMOTE OPERATION")

Use of remotely controlled sensors and actuators allowing a human to operate equipment even though the human presence is removed from the work site. Refers to controlling the motion of a complex piece of equipment such as a mechanical arm, rather than simply turning a device on or off from a distance. The human is provided with some information feedback, e.g. visual, force, or tactile, that enables him to safely and effectively operate the equipment by remote control.

AUGMENTED TELEOPERATOR

A teleoperator with sensing and computation capability that can carry out portions of a desired operation without requiring detailed operator control. The terms "teleautomation" and "tele-robotics" have been used here.

TELEPRESENCE ("REMOTE PRESENCE")

The ability to transfer a human's sensory perceptions, e.g., visual, tactile, to a remote site for the purpose of improved teleoperation performance. At the worksite, the manipulators have the dexterity to allow the operator to perform normal human functions. At the control station, the operator receives sufficient quantity and quality of sensory feedback to provide a feeling of actual presence at the worksite.

ROBOT

A generic term, connoting many of the following ideas: A mechanism capable of manipulation of objects and/or movement having enough internal control, sensing, and computer analysis so as to carry out a a more or less sophisticated task. The term usually connotes a certain degree of autonomy, and an ability to react appropriately to changing conditions in its environment. Robotics is a specialize discipline within the broader fields of autonomy and automation.

ARTIFICIAL INTELLIGENCE

Artificial Intelligence is the part of computer science concerned with the design and implementation of programs that make complicated decisions, learn or become more adept at making decisions, interact

with humans in a way natural to humans, and in general exhibit the characteristics we associate with intelligence in human behavior. "Intelligence", as used here, is the ability to meet and cope with novel situations by adjusting behavior, the ability to comprehend the interrelationships between facts and concepts, and the ability to generate new concepts and relationships from those already known, i.e., already in the data base. "Artificial", as used here indicates that the intelligence is achieved by means of a computer or electro-mechanical-optical device.

KNOWLEDGE ENGINEERING

The discipline involved with extracting, articulating, and computerizing an expert's knowledge. Knowledge engineering addresses the problem of building skilled computer systems, aiming first at extracting the expert's knowledge and then organizing it in an effective implementation.

EXPERT SYSTEM

An expert or knowledge-based system is one that stores, processes, and utilizes significant amount of information about a particular domain to solve problems or answer questions in that domain. The system is able to perform at the level of an experienced human practitioner in that domain of knowledge.

new additions suggested by Martin

REMOTE CONTROL

The capability to control from a remote location. The terms telepresence, teleoperation, supervisory control, teleautomation, and augmented control as used in the literature are generally regarded as different examples or subsets of remote control.

SUPERVISORY CONTROL

A control mode using a mix of human and machine control in which the operator uses high-level commands when instructing the computer to perform complex multiple activity sequences.

TELEAUTOMATION

The capability to interact with and modify a remote automated system and carry out a predesigned function or series of actions after initiation by an external stimulus.

HYBRID ROBOT

A robotic device that normally runs under preprogrammed control but which when required can easily and adeptly act as a teleoperator/ telepresence device.

LIST OF ABBREVIATIONS AND ACRONYMS

AFSD	U.S. Air Force Space Division	LEO	Low Earth Orbit
AI	Artificial Intelligence	MM	Martin Marietta Aerospace Company
CCTV	Closed Circuit Television	MIT	Massachusetts Institute of Technology
COR	Contracting Officer's Representative	MMS	Multi-Mission Modular Spacecraft
CSI	California Space Institute	MMU	Manned Maneuvering Unit
DoD	U.S. Department of Defense	MPF	Materials Processing Facility (Free Flying)
DS	(Space Station) Data System	MSFC	Marshall Space Flight Center
EVA	Extra-Vehicular Activity	NASA	National Aeronautics & Space Administration
FSS	Flight Support System	OMV	Orbital Maneuvering Vehicle
GE	General Electric Company	ORU	Orbital Replacement Unit
GEO	Geosynchronous Earth Orbit	OTV	Orbital Transfer Vehicle
GM	General Motors, Inc.	PFR	Portable Foot Restraint
GRO	Gamma Ray Observatory	RMS	Remote Manipulator System
GSFC	Goddard Space Flight Center	S/C	Spacecraft
HO	Human Operator	SS	Space Station
HQ	NASA Headquarters	SMM	Solar Maximum Mission (Spacecraft)
IOC	Initial Operational Capability	STS	Space Transportation System (Shuttle)
IR&D	Independent Research and Development	T/M	Telemetry
IVA	Intra-Vehicular Activity	T/O	Teleoperator
JSC	Johnson Space Center	VHSIC	Very High Speed Integrated Circuits

GE SSAS SPACE MANUFACTURING CONCEPTS

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